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A STATISTICAL MODEL OF RADAR BIRD CLUTTER AT THE DEW LINE

John Antonucci

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13. ABSTRACT (Maximum 200 words)
The Distant Early Warning (DEW) line radar system is presently being upgraded. One of the problems encountered is radar bird clutter. In this report we consider radar bird clutter during migration of a number of species of large birds, and present an estimation of the Radar Cross Section (RCS) as the number of birds, the number of flocks, and the number density of a flock, expected to be seen are mathematically described. Probabilistic descriptions are developed of the bird clutter that the radars are expected to observe. The probability that a flock of a known species of birds would have a particular RCS is determined. Also, probability curves are derived that predict how many flocks out of those observed would have an RCS greater than a specified arbitrary value. A mathematical procedure to make these predictions is established.

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1. INTRODUCTION

About a dozen years ago the Air Force Systems Command began an effort to improve the Distant Early Warning (DEW) line radar system by incorporating new radars with superior performance. The Air Force is particularly concerned with improving the performance of the system in the presence of radar clutter. One serious source of radar clutter at the DEW line comes from the presence of birds. In this report we consider radar bird clutter and present an estimation of the radar cross section (RCS) due to birds that the DEW line radars are expected to encounter. We develop a mathematical description of the migration parameters and use distribution functions and probability theory to indicate the probability of an event occurring; the event being some depiction of the radar cross section of flocks of birds.

In an earlier report[1], the time periods, numbers, and migration parameters of birds migrating across the DEW line were compiled. Much of the data indicating the seasonal time periods and the number of birds expected to migrate across the DEW line area is reproduced here and shown in Tables 1A through 1H[2]. The area is a band about 2 degrees of latitude wide that extends across the length of the DEW line and is centered at the radar sites. There are

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1 Antonucci, J.D. (1981) *Radar Bird Clutter at the DEW Line*, RADC-TR-81-177, ADB0609016.

2 Bellrose, F.C. (1978) *Ducks, Geese and Swans of North America*, 2nd Ed., Revised, Stockpole Books, Harrisburg, PA

numerous species of birds in the arctic. However, we concentrated on the larger size birds because they are expected to have the most significant effect on the radar observations.

Table 1a. Migration Periods and Numbers of Ducks, Swans, and Geese Migrating past the DEW Line Area. The horizontal bars indicate the expected period of migration. North Alaska ---- Fall

Name	July	Aug	Sept	Oct	N_0 - Total No. of Birds Passing*
Eider					1,108,000
Brant					50,000
Lesser Snow Goose					30,000
White Fronted Goose					50,000
Oldsquaw					125,000
Pintail					120,000
Whistling Swan					1,000

*Standard area defined in text.

Table 1b. Migration Periods and Numbers of Ducks, Swans, and Geese Migrating past the DEW Line Area. The horizontal bars indicate the expected period of migration. Western Canada---- Fall

Name	July	Aug	Sept	Oct	N_0 - Total No. of Birds Passing
Eider					1,108,000
Brant					20,000
Lesser Snow Goose					250,000
White Fronted Goose					60,000
Oldsquaw					300,000
Pintail					200,000
Whistling Swan					21,000

Table 1c. Migration Periods and Numbers of Ducks, Swans, and Geese Migrating past the DEW Line Area. The horizontal bars indicate the expected period of migration. Central Canada---- Fall

Name	July	Aug	Sept	Oct	N_0 - Total No. of Birds Passing
Eider					1,000,000
Brant					7,000
Lesser Snow Goose					24,000
White Fronted Goose					15,000
Oldsquaw					100,000
Pintail					2,000
Whistling Swan					1,200

Table 1d. Migration Periods and Numbers of Ducks, Swans, and Geese Migrating past the DEW Line Area. The horizontal bars indicate the expected period of migration. Eastern Canada---- Fall

Name	July	Aug	Sept	Oct	N_0 - Total No. of Birds Passing
Eider					100,000
Lesser Snow Goose					50,000
Oldsquaw					500,000
Whistling Swan					5,000
Greater Snow Goose					100,000

Table 1e. Migration Periods and Numbers of Ducks, Swans, and Geese Migrating past the DEW Line Area. The horizontal bars indicate the expected period of migration. North Alaska---- Spring

Name	Apr	May	June		N_0 - Total No. of Birds Passing
Eider					1,108,000
Brant					50,000
Lesser Snow Goose					30,000
White Fronted Goose					50,000
Oldsquaw					125,000
Pintail					120,000
Whistling Swan					1,000

Table 1f. Migration Periods and Numbers of Ducks, Swans, and Geese Migrating past the DEW Line Area. The horizontal bars indicate the expected period of migration. Western Canada---- Spring

Name	Apr	May	June		N_0 - Total No. of Birds Passing
Eider					1,108,000
Brant					20,000
Lesser Snow Goose					250,000
White Fronted Goose					60,000
Oldsquaw					300,000
Pintail					200,000
Whistling Swan					21,000

Table 1g. Migration Periods and Numbers of Ducks, Swans, and Geese Migrating past the DEW Line Area. The horizontal bars indicate the expected period of migration. Central Canada---- Spring

Name	Apr	May	June		N_0 - Total No. of Birds Passing
Eider					1,000,000
Brant					7,000
Lesser Snow Goose					24,000
White Fronted Goose					15,000
Oldsquaw					100,000
Pintail					2,000
Whistling Swan					1,200

Table 1h. Migration Periods and Numbers of Ducks, Swans, and Geese Migrating past the DEW Line Area. The horizontal bars indicate the expected period of migration. Eastern Canada---- Spring

Name	Apr	May	June		N_0 - Total No. of Birds Passing
Eider					100,000
Lesser Snow Goose					50,000
Oldsquaw					500,000
Whistling Swan					5,000
Greater Snow Goose					100,000

2. ANALYTICAL DESCRIPTION OF BIRD MIGRATION PARAMETERS THAT RELATE TO RADAR CROSS SECTION

In this section, we investigate the parameters that determine the flock's RCS, and the probability of its occurrence. We obtain the bird's RCS, and incorporate it in the description of the radar cross section distribution of a flock in flight, and we also obtain the distribution of the bird density of a flock. The two distributions combined give us the expectations of the flock's RCS, or, more specifically, the probability of observing a flock with a specified RCS. To determine the probability of observing a particular number of flocks with a certain RCS we must know the number of birds present, the number of flocks that may form, and the distribution of the flock's number density. In short, we describe analytically the desired parameters, and then use the analytic description to obtain the number of birds per day, the number of birds on the radar screen, the density of the flock, and the RCS of a bird. These values are then used to determine the extent of the radar cross sections that the radars are expected to encounter.

2.1. Number of Birds Per Day

First, we try to put the data of the birds migrating across the DEW line in analytical form. The tables indicate generally the period within which the birds migrate, although not at a uniform rate. Of any one species of birds, some begin traveling earlier than others, then there would be a time of heavy migration, and finally there would be some who leave later. Environmental conditions, especially weather, act to influence the rate of migration. The temporal variation of the number of birds per day migrating through the DEW Line is somewhat symmetrical about a peak period. As an estimation, we express the migration rate as a normal distribution curve. Although the normal distribution curve is a probability curve, we can use the equation to portray the number of birds per day.

If the number of birds per day is $f_1(x)$, and x is the day of travel, then

$$\int_{x_1}^{x_2} f_1(x)\, dx = n \tag{1}$$

which is the number of birds traveling during the time period, x_2-x_1.

During the migration period G, the total number of birds traveling is N_0 (N_0 is included in the tables). Therefore

$$\int_{0}^{G} f_1(x)\, dx = N_0\ . \tag{2}$$

Let $\frac{f_1(x)}{N_0} = f(x)$, the fractional number of birds per day, follow a normal density function. Then

$$f(x) = \frac{1}{s\sqrt{2\pi}} e^{-(1/2)((x-a)/s)^2} \tag{3}$$

and the number of birds traveling, F(x), can be approximated by the probability function, and used from minus infinity instead of from zero. F(x) is given by

$$f(x) = \int_{-\infty}^{x} f(x)\,dx \tag{4}$$

where x is the day of travel (x=0 is the beginning of the migration period), a is the mean, and s is the standard deviation. We assume that close to 100 percent of the birds leave over the span of the migration period. If plus and minus three standard deviations cover the migration period G, then 99.7 percent of the birds would have left in that time. Most leave within plus and minus one standard deviation. For typical data in which the migration period was 42 days, and the standard deviation was 7 days, then 68 percent of the birds would leave within the middle 14 days. Since our parameter is G, we would like to express $f_1(x)$ in terms of G. Having x=0 at the beginning of the migration period, and considering that a=G/2 and s=G/6, then, in terms of G

$$f_1(x) = \frac{6N_0}{G\sqrt{2\pi}} e^{-(1/2)[(6x/G)-3]^2} . \tag{5}$$

To obtain the peak value of birds traveling in a day, N_p, we use Eq. (1) with $x_1 = a - 1/2$ and $x_2 = a + 1/2$. Then

$$N_p = \int_{a-1/2}^{a+1/2} \frac{6N_0}{G\sqrt{2\pi}} e^{-(1/2)[(6x/G)-3]^2} dx . \tag{6}$$

To put this in a form suitable for use with the normal distribution tables, we let u = (6 x/G)- 3; and, for convenience, we let x go from a to a + 1/2 and multiply the integral by 2. Then Eq. (6) reduces to:

$$N_p = 2N_0 \int_0^{3/G} \frac{1}{\sqrt{2\pi}} e^{-(1/2)\,u^2}\, du\,. \tag{7}$$

As an alternative to using the tables, a good approximation to the integral is to calculate the rectangle under the peak of the curve. This would be $f_1(x)$ at $x = a + 1/2$, the height, and multiplying by Δx, equal to 1, the width for one day.

$$\left[f_1(a+1/2)\right] \Delta x \cong \frac{6N_0}{G\sqrt{2\pi}} e^{-1/2(3/G)^2}\,. \tag{8}$$

Tables 2A through 2H indicate the maximum number of birds, N_p, per day.

Table 2a. Appearance on Radar of Birds Migrating Past the DEW Line. North Alaska ---- Fall

Name	Distance First Seen by Radar (km)	Time on Radar Screen (hr)	Maximum Birds/Day (N_p)	Number of Birds on Radar Screen (N_s)
Eider	48	1.2	34660	3900
Brant	53	1.1	4280	440
Lesser Snow Goose	130	3.2	2060	620
White Fronted Goose	130	3.2	2860	860
Oldsquaw	48	1	10700	1000
Pintail	53	1.3	6870	840
Whistling Swan	156	3.9	86	32

Tables 2b. Appearance on Radar of Birds Migrating past the DEW Line. Western Canada ---- Fall

Name	Distance First Seen by Radar (km)	Time on Radar Screen (hr)	Maximum Birds/Day (N_p)	Number of Birds on Radar Screen (N_s)
Eider	87	2.2	34660	7150
Brant	92	1.8	1710	290
Lesser Snow Goose	142	3.6	17150	5790
White Fronted Goose	142	3.6	3435	1160
Oldsquaw	87	1.7	25680	4100
Pintail	92	2.3	11450	2470
Whistling Swan	170	4.2	1800	710

Table 2c. Appearance on Radar of Birds Migrating Past the DEW Line. Central Canada ---- Fall

Name	Distance First Seen by Radar (km)	Time on Radar Screen (hr)	Maximum Birds/Day (N_p)	Number of Birds on Radar Screen (N_s)
Eider	87	2.2	31280	6450
Brant	92	1.8	600	100
Lesser Snow Goose	135	3.4	1650	525
White Fronted Goose	135	3.4	860	275
Oldsquaw	87	1.7	8560	1365
Pintail	92	2.3	115	25
Whistling Swan	160	4	105	40

Table 2d. Appearance on Radar of Birds Migrating Past the DEW Line. Eastern Canada ---- Fall

Name	Distance First Seen by Radar (km)	Time on Radar Screen (hr)	Maximum Birds/Day (N_p)	Number of Birds on Radar Screen (N_s)
Eider	118	2.9	3130	850
Lesser Snow Goose	205	5.1	3430	1640
Oldsquaw	118	2.4	42800	9630
Whistling Swan	232	5.8	430	235
Greater Snow Goose	205	5.1	8560	4100

Table 2e. Appearance on Radar of Birds Migrating Past the DEW Line. North Alaska ---- Spring

Name	Distance First Seen by Radar (km)	Time on Radar Screen (hr)	Maximum Birds/Day (N_p)	Number of Birds on Radar Screen (N_s)
Eider	48	1.2	47625	5360
Brant	53	1.1	5680	585
Lesser Snow Goose	130	3.2	2570	770
White Fronted Goose	130	3.2	4280	1285
Oldsquaw	48	1	10700	1000
Pintail	53	1.3	6870	840
Whistling Swan	156	3.9	86	32

Table 2f. Appearance on Radar of Birds Migrating Past the DEW Line. Western Canada ---- Spring

Name	Distance First Seen by Radar (km)	Time on Radar Screen (hr)	Maximum Birds/Day (N_p)	Number of Birds on Radar Screen (N_s)
Eider	87	2.2	63430	13080
Brant	92	1.8	2275	385
Lesser Snow Goose	142	3.6	21400	7225
White Fronted Goose	142	3.6	5140	1735
Oldsquaw	87	1.7	25680	4100
Pintail	92	2.3	11450	2470
Whistling Swan	170	4.2	1800	710

Table 2g. Appearance on Radar of Birds Migrating Past the DEW Line. Central Canada ---- Spring

Name	Distance First Seen by Radar (km)	Time on Radar Screen (hr)	Maximum Birds/Day (N_p)	Number of Birds on Radar Screen (N_s)
Eider	87	2.2	49100	10125
Brant	92	1.8	800	135
Lesser Snow Goose	135	3.4	2730	870
White Fronted Goose	135	3.4	1285	410
Oldsquaw	87	1.7	8560	1365
Pintail	92	2.3	115	25
Whistling Swan	160	4	105	40

Table 2h. Appearance on Radar of Birds Migrating
Past the DEW Line. Eastern Canada ---- Spring

Name	Distance First Seen by Radar (km)	Time on Radar Screen (hr)	Maximum Birds/Day (N_p)	Number of Birds on Radar Screen (N_s)
Eider	118	2.9	4910	1290
Lesser Snow Goose	205	5.1	5680	2715
Oldsquaw	118	2.4	42800	9630
Whistling Swan	232	5.8	430	235
Greater Snow Goose	205	5.1	11360	5430

2.2. Number of Birds on the Radar Screen

A radar designer may be interested in applying the above determinations in a number of different ways. As an example, we chose, in our particular case, to consider the number of birds on the radar screen. This approach is particularly useful for tracking.

To determine the number of birds appearing on the radar screen, we first consider the flight period within a day. A migrating species of birds does not travel during all 24 hours of a day. Observations of migrating birds have indicated that a large majority of them may travel for 10 to 14 hours of the day. Also, most travel takes place at a constant rate over a good portion of the time. In light of the data, it is reasonable to assume that 3/4 of the birds travel constantly over an 8 hour period. Therefore, the maximum number of birds traveling per hour is $(3/4)\ N_p\ /8$. How long they appear on the radar screen depends on their distance when first seen above the horizon, and on their flying speed. If the distance from the horizon to the radar is d_1 and the distance beyond the horizon to the birds is d_2 then, $d_1 + d_2$, or D, is the distance from the radar to the birds.

$$D = \sqrt{2rh_1+h_1^2} + \sqrt{2rh_2+h_2^2} \tag{9}$$

where r is the radius (4000 mi) of the earth, h_1 is the height of the antenna above sea level, and h_2 is the altitude of the migrating birds. The heights of the antennas, which are on towers, vary across the DEW line. The long range antenna towers are 66 feet tall, and most of the short range antenna towers are 100 feet. Also, the towers are located on terrain at various levels above sea level. Our present effort does not deal with each site. Instead, the DEW line is treated as divided into four sections, and for each section a nominal antenna height, favoring the worst case, is used. The antenna heights for Alaska for the long range radar (200 miles) and the short range radar (70 miles) were 130 feet and 200 feet respectively. The short range antenna was used for the lower flying birds since their first appearance was within its range. The typical flying altitude of the migrating Eider and Oldsquaw is 100 ft., and the Brant and Pintail is 150 ft. The typical flying altitude of the Lesser Snow Goose, White Fronted Goose, and the Greater Snow Goose was estimated as 2900 ft., and the Whistling Swan as 4500 ft. The 130 foot height was used for these higher flying birds since the long range antenna was located at that level, and when the birds first appeared they were beyond the 70 mile range, but within the 200 mile range. For western and central Canada, the 1150 foot antenna height was used for the lower flying birds and 325 foot and 200 foot heights respectively for the higher flying birds. In eastern Canada, a height of 2450 feet was used. The birds' time, T, on the radar screen is 2D divided by their speed. (This is actually the time it takes to travel across the full length of the screen. There is not enough data that may be used to describe birds traveling across segments of the radar coverage. We use the full length of the screen as a first order approximation). The migration speeds of the Brant and Oldsquaw were taken as 60 mph, and the others were 50 mph. The number of birds, N_s , in the radar coverage is equal to the number of birds per hour times the time in the radar coverage, or:

$$N_s = \frac{3}{4}\frac{1}{8} N_p T . \tag{10}$$

Tables 2A through 2H indicate the calculated values of N_s and the associated parameters.

2.3 Number Density of a Flock

Another parameter affecting the RCS is the bird density of a flock. Much of the observed data has indicated a non-symmetrical distribution of bird densities. There are more flocks with a high, rather than low, number of birds. There is a range of densities which have the greatest chance of occurring and this we refer to as the usual flock size. For instance, the usual bird densities of Eiders are between 25 and 100, but there are densities as high as 1000 and as low as 10. Any number of skewed distribution functions can be used to reasonably fit the data. We assume here that the number of birds in a flock, y, follows a log normal distribution. The curve is positive and skewed such that the higher density values are more or less included. The log normal distribution function, f(y), is given by:

$$f(y) = \frac{1}{y\beta\sqrt{2\pi}} e^{-(1/2)\left\{[\ln(y)-\alpha]/\beta\right\}^2} . \tag{11}$$

This follows a normal distribution when z=ln y. In the normal function, the most probable value M0, the median M1, and the mean μ, are coincident. In the log normal distribution, these values are dispersed, and are given by the following expressions:

$$M0 = e^{\left(\alpha - \beta^2\right)} \tag{12}$$

$$M1 = e^{\alpha} \tag{13}$$

$$\mu = e^{\left(\alpha + \beta^2/2\right)} . \tag{14}$$

The three factors are interrelated by, $M1^3 = \mu^2$ M0, and the median lies between the mode and mean values. By adjusting any two of these parameters, the curve can be varied to fit the data. For example, a flock of Eiders, which usually has between 25 and 100 birds, at times can extend from 10 to 1000. The log normal distribution function that best fits this data results in a median of 90 and a mean of 135. The area within portions of the curve was obtained by using the relationship between the log normal and the normal distribution functions. By using the parameter $(\ln(y) - \alpha)/\beta$, in the normal distribution tables, the area between y_1 and y_2 of the log normal curve can be obtained. For the Eider, with the values of the median and mean chosen, the percent of the area between 25 and 100 is 47 percent, the area less than 10 is 0.7 percent, and greater than 1000 is 0.4 percent. This data fitting procedure was carried out for each case and the results are tabulated in Table 3.

Table 3. Bird Density Log Normal Distribution Parameters

Name	Adult Typical Weight (gm)	Bird Radar Cross Section, σ_B (m^2)	
		λ = 25 cm	λ = 75 cm
Eider	2020	0.0174	0.0324
Brant	1480	0.0157	0.0174
Lesser Snow Goose	2630	0.0190	0.0549
White Fronted Goose	2680	0.0191	0.0573
Oldsquaw	870	0.0131	0.0060
Pintail	950	0.0135	0.0072
Whistling Swan	6810	0.0261	0.0782
Greater Snow Goose	3070	0.0200	0.0600

2.4. Mean Radar Cross Section of a Bird

Another significant quantity is a bird's mean RCS, σ_1. A number of bird RCS measurements have been reported in the literature. Pollon[3] gathered the existing data and plotted, a normalized σ_1 as a function of wavelength and weight. His plot is shown here in Figure 1. The section of the graph with the positive slope, Section 1, depicts the beginning of the optical region, and the interference region without the oscillations. The negative slope section of the graph, Section 2, is the Rayleigh region. The Rayleigh region follows the σ_1 versus λ^{-4} dependency (λ being the wavelength). However, Section 1 follows a σ_1 versus λ dependency, which is steeper than would be expected. This may be attributed to the fact that the cross section has a log normal dependency. To gain insight into the graph and recognize its limitations, we have compared other cases with it. The RCS of a bird, modelled as an equivalent metal sphere, is found to follow the same shape as the metal sphere's RCS σ_s curve, but, is equal to 0.54 σ_s. This general behavior is also apparently true when using a prolate spheroid model of a bird. In Figure 1, the RCS of a metal sphere would have a shallow slope in Section 1, and approach 0 dB, the limit of the optical region. The birds' RCS would approach 10 log (0.54) or −2.67 dB. Comparatively, this section of Pollon's graph is steeper and goes significantly lower, to approximately -7dB. We found that we did not have to use the curve below $\lambda/w^{1/3}$ (w being the weight of the bird) equal to 1, where the curve is more questionable.

[3] Pollon, G.E. (1972) Distribution of radar angels, *IEEE Trans. AES*, **AES-8**:721-727.

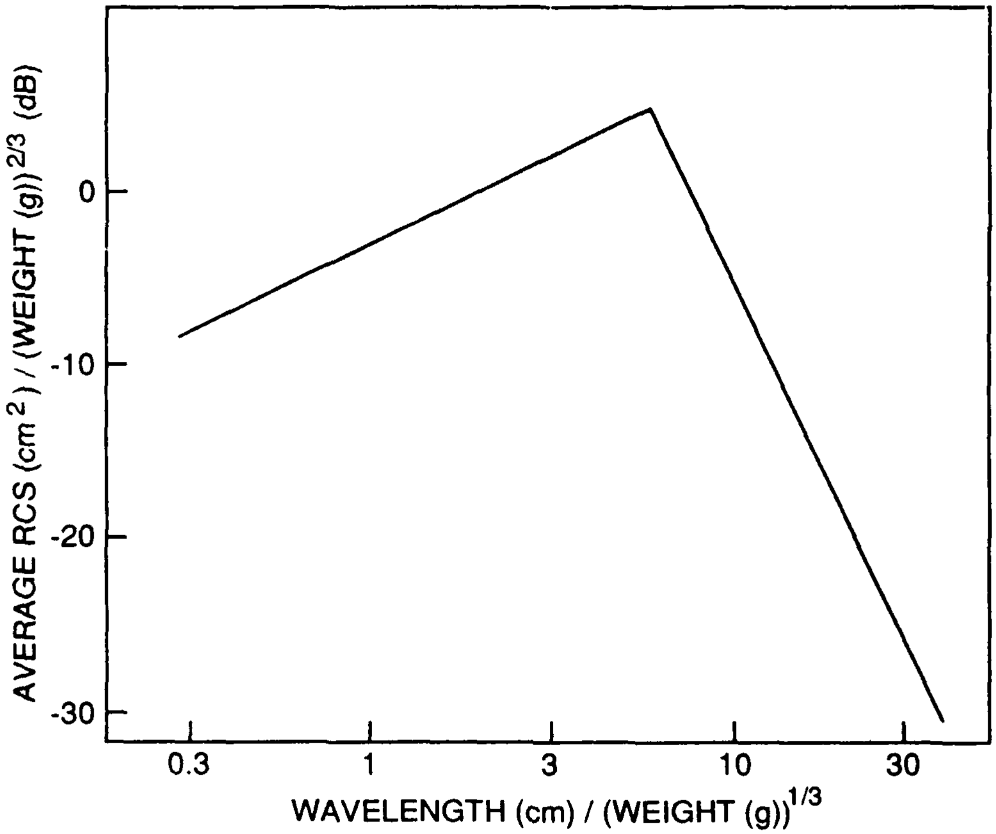

Figure 1. Normalized Bird Mean Radar Cross Section (After G.E. Pollon[3])

To calculate σ_1 from the graph, we set up an equation for each straight line. Taking into account the log scale used by Pollon, we used the equation:

$$10 \log \left(\sigma_1/w^{2/3}\right) = m \log \left(\lambda/w^{1/3}\right) + b \tag{15}$$

where m is the slope, and b is the intersection on the ordinate, with the coordinate axis origin being at the 0.1 point of the graph. It follows that:

$$\sigma_1 = \lambda^{m/10}\, 10^{b/10}\, w^{(2/3-m/30)} . \tag{16}$$

For the first part of the graph, m=10, and b=-2.6. Therefore, for $\lambda/W^{1/3} < 0.54$:

$$\sigma_1 = 0.55\, W^{1/3}\, \lambda \tag{17}$$

in which it is seen that σ varies as λ. In the second curve, m = –40 and b = 34 . Therefore, for $\lambda/W^{1/3} > 0.54$:

$$\sigma_1 = 2512\, w^2\, \lambda^{-4}. \tag{18}$$

Where σ_1 varies as λ^{-4}, a known dependency in the Rayleigh region. The value of σ was obtained for both λ equal to 25 cm and 75 cm, using the weight, w, as a variable. Although 400 MHz is not used at the DEW line, it is included here to show the effect of frequency. Also, it is worthwhile, since UHF frequencies are generally applicable to airborne target detection, especially low RCS targets. Graphs were generated, and the plots are shown in Figure 2. The typical weight and cross section for each species of bird are indicated in Table 4. It is worthwhile noting, that in the interference region, σ_1 increases with wavelength by the relationship:

$$\sigma_2 = \sigma_1 \lambda_2 / \lambda_1 . \tag{19}$$

The subscripts 1 and 2 refer to the two different frequencies.

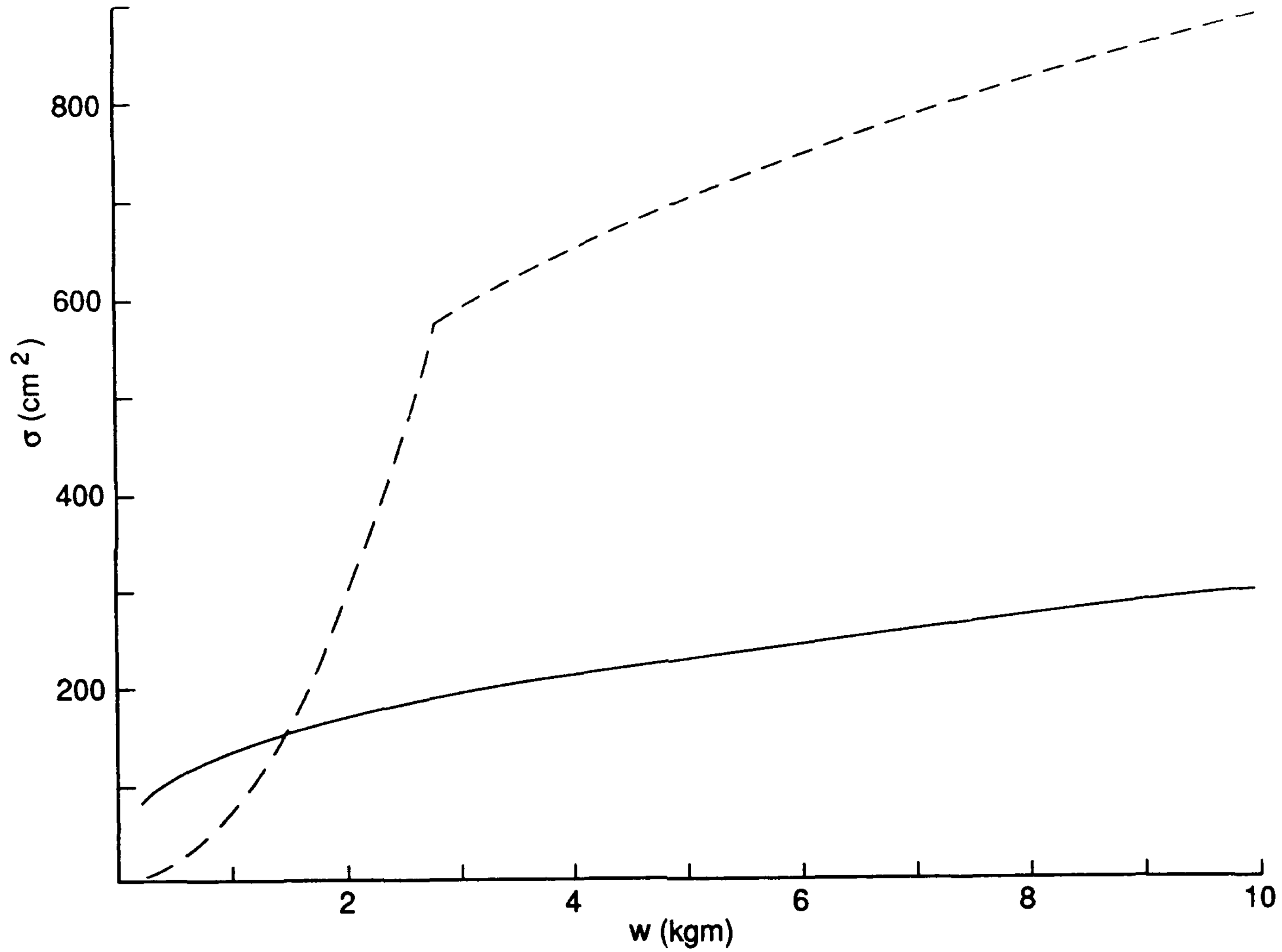

Figure 2. Mean Radar Cross Section of a Bird as a Function of Bird Weight. Solid line is for frequency of 1200 MHz, dashed line is for frequency of 400 MHz.

Table 4. Bird Mean Radar Cross Section

Name	Usual Bird Density (Birds/Flock)	Bird Density Log Normal Distribution Parameters		
		Mode, M0	Median, M1	Mean, μ
Elder	25 - 100	40	90	135
Brant	200 - 1000	389	850	1257
Lesser Snow Goose	100 - 1000	438	570	650
White Fronted Goose	50 - 100	66	75	80
Oldsquaw	50 - 200	111	130	141
Pintail	20 - 70	35	45	51
Whistling Swan	25 - 100	48	63	72
Greater Snow Goose	35 - 400	145	200	235

3. PROBABILITY THAT AN OBSERVED FLOCK HAS A SPECIFIED RADAR CROSS SECTION

It is necessary for a radar system designer to know the chances of being presented with a certain amount of clutter. Here, we consider clutter from a flock of birds during the migration season. We assume the peak time period of the season, so we may postulate the appearance of a flock of birds. If a flock of a particular species of birds is observed, then what is the probability that the flock will have a specified cross section σ_0 ? To determine this, we must obtain the probability that a given density flock will have the cross section σ_0 , and also the probability that the flock will have a particular density. The probability of both occurring together is given by the product of the two probabilities. If the flocks have a spread of densities, then the total probability of occurrence is the sum over each flock density. The same procedure is done for cross sections greater than the specified value.

The probability P(N), that there are N_1 birds in the flock, from Eq. (11), is:

$$P(N_1) = \frac{1}{N_1 \beta \sqrt{2\pi}} e^{-(1/2)\left((\ln(N_1)-\alpha)/\beta\right)^2} dN . \tag{20}$$

For simplicity, we may assume that each bird in the flock has the same cross section σ_1, and, therefore, the flock's mean cross section is $N_1\sigma_1$. The voltage amplitude of backscatter of a flock is Rayleigh distributed. Therefore, the flock RCS σ, being a function of power, is exponentially distributed. If the number of birds in the flock is N_1, then the conditional probability that σ is σ_0 is

$$P(\sigma_0 | N_1) = \frac{1}{N_1 \sigma_1} e^{-\sigma_0 / N_1 \sigma_1} d\sigma \tag{21}$$

where $N_1\sigma_1$ is the mean. The probability that there are N_1 birds in the flock, and the RCS is σ_o is $P(\sigma_0/N_1)\ P(N_1)$. Hence, from Eqs. (20) and (21)

$$P(\sigma_0 | N_1)\ P(N_1) = \left[\frac{1}{N_1 \sigma_1} e^{-\sigma_0 / N_1 \sigma_1} d\sigma\right]\left[\frac{1}{N_1 \beta\sqrt{2\pi}} e^{-(1/2)\left\{\left[\ln(N_1)-\alpha\right]/\beta\right\}^2} dN\right]. \tag{22}$$

The probability that there are N_1 birds, and the RCS is greater than σ_0 is:

$$P = \left[\int_{\sigma_0}^{\infty} \frac{1}{N_1 \sigma_1} e^{-\sigma_0 / N_1 \sigma_1} d\sigma\right]\left[\frac{1}{N_1 \beta\sqrt{2\pi}} e^{-(1/2)\left\{\left[\ln(N_1)-\alpha\right]/\beta\right\}^2} dN\right]. \tag{23}$$

The probability that there are any number of birds N, and σ is greater than σ_0 is:

$$L(\sigma_0) = \int_{N=0}^{\infty} \int_{\sigma=\sigma_0}^{\infty} \frac{1}{N\sigma_1} e^{-\sigma/N\sigma_1} \frac{1}{N\ \beta\sqrt{2\pi}} e^{-(1/2)\left\{\left[\ln(N)-\alpha\right]/\beta\right\}^2} d\sigma\, dN \tag{24}$$

$$L(\sigma_0) = \int_{N=0}^{\infty} \frac{1}{N\beta\sqrt{2\pi}} e^{-(1/2)\left\{\left[\ln(N)-\alpha\right]/\beta\right\}^2} \left(\frac{1}{N\sigma_1}\right) \int_{\sigma_0}^{\infty} e^{-\sigma/N\sigma_1}\, d\sigma\, dN. \tag{25}$$

Equation (25) simplifies to:

$$L(\sigma_0) = \int_0^\infty \frac{1}{N\beta\sqrt{2\pi}}\, e^{-\sigma/N\sigma_1}\, e^{-(1/2)\{[\ln(N)-\alpha]/\beta\}^2}\, dN \tag{26}$$

after integrating the inner integral with respect to σ.

The integral in Eq. (26) was evaluated using Simpson's rule[4]. The probability, L, of the flock's RCS being greater than σ_0 was determined as a function of σ_0, and the results are shown in Figures 3A through 3H. As an example, reading from the graph, a flock of Eiders observed at 1200 MHz has a probability of approximately 0.5 that the flock has a RCS greater than 1 m^2.

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4 Suggested by Dr. Jay Schindler, Laboratory Director of RADC/EE, during private conversation.

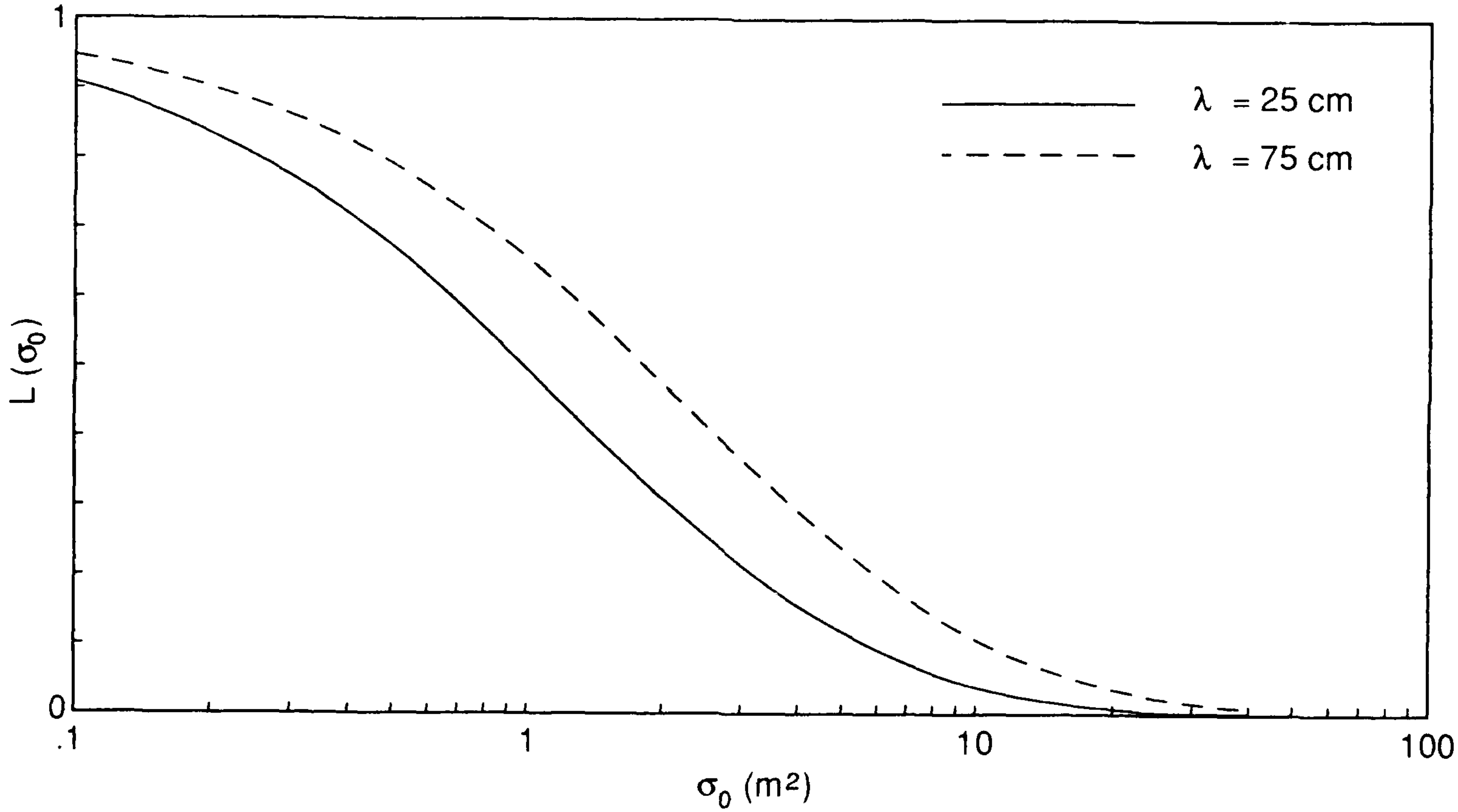

Figure 3a. The Probability That a Flock Has a Mean Radar Cross Section Equal to or Greater Than a Specified Value, σ_0. Eider.

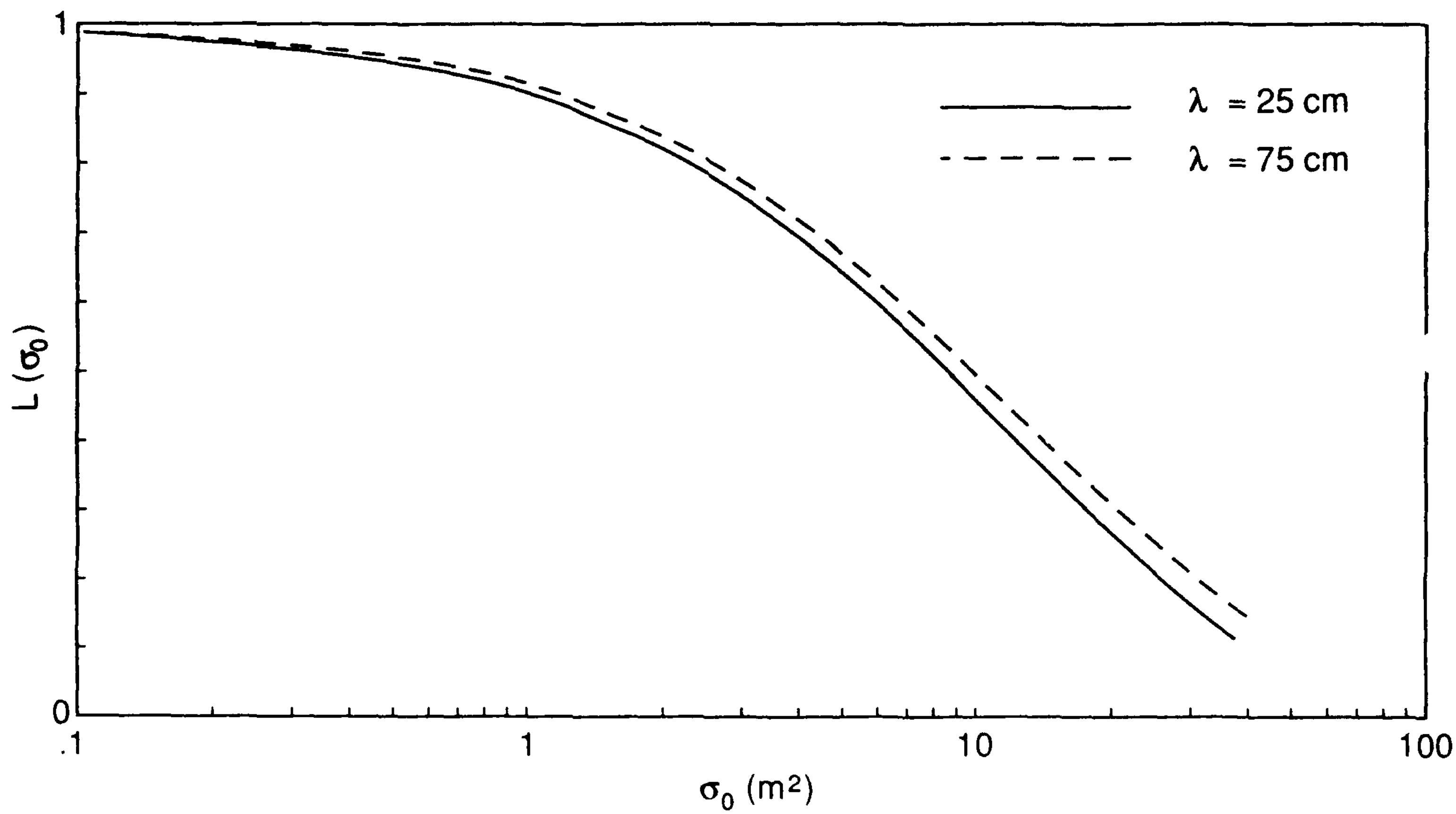

Figure 3b. The Probability That a Flock Has a Mean Radar Cross Section Equal to or Greater Than a Specified Value, σ_0. Brant.

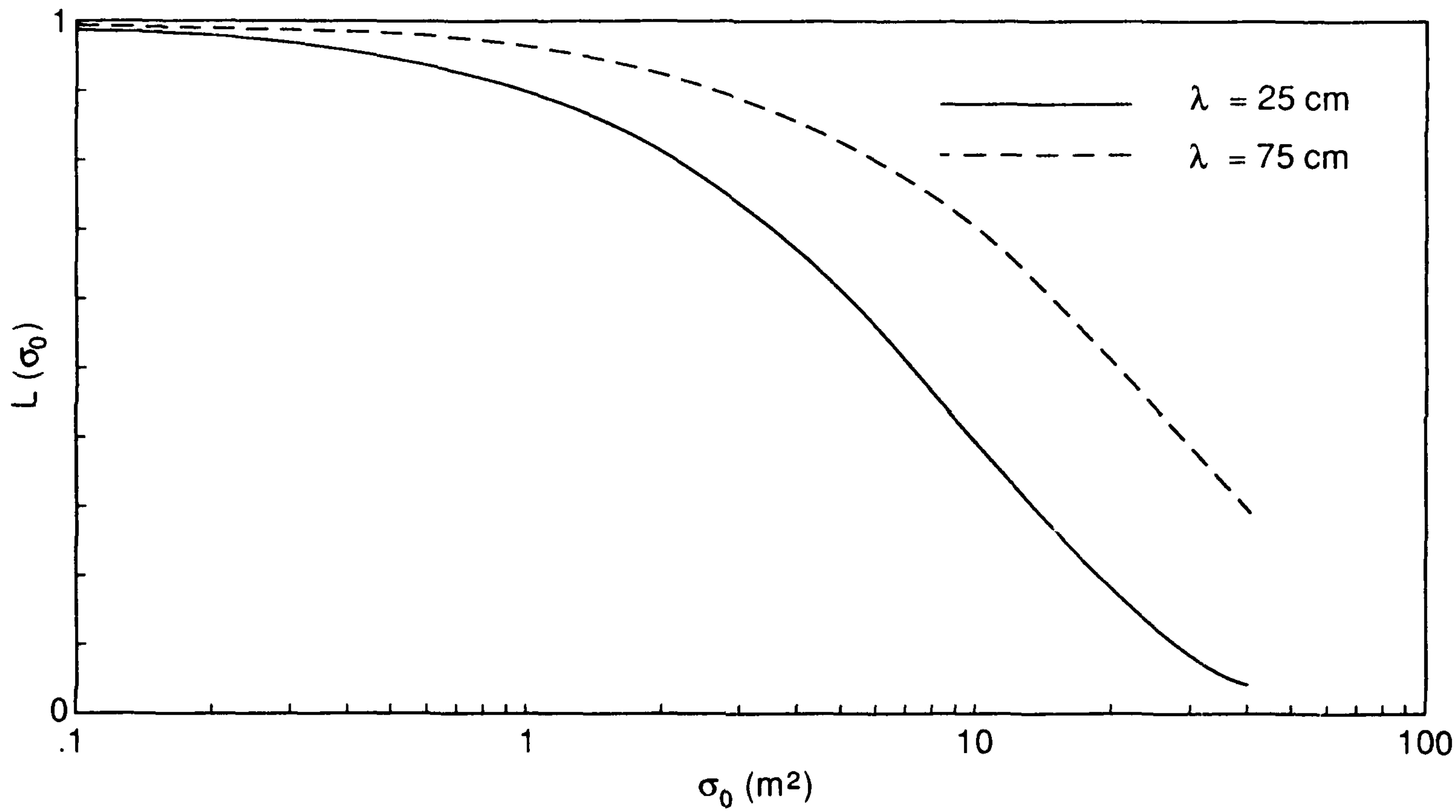

Figure 3c. The Probability That a Flock Has a Mean Radar Cross Setion Equal to or Greater Than a Specified Value, σ_0. Lesser Snow Goose.

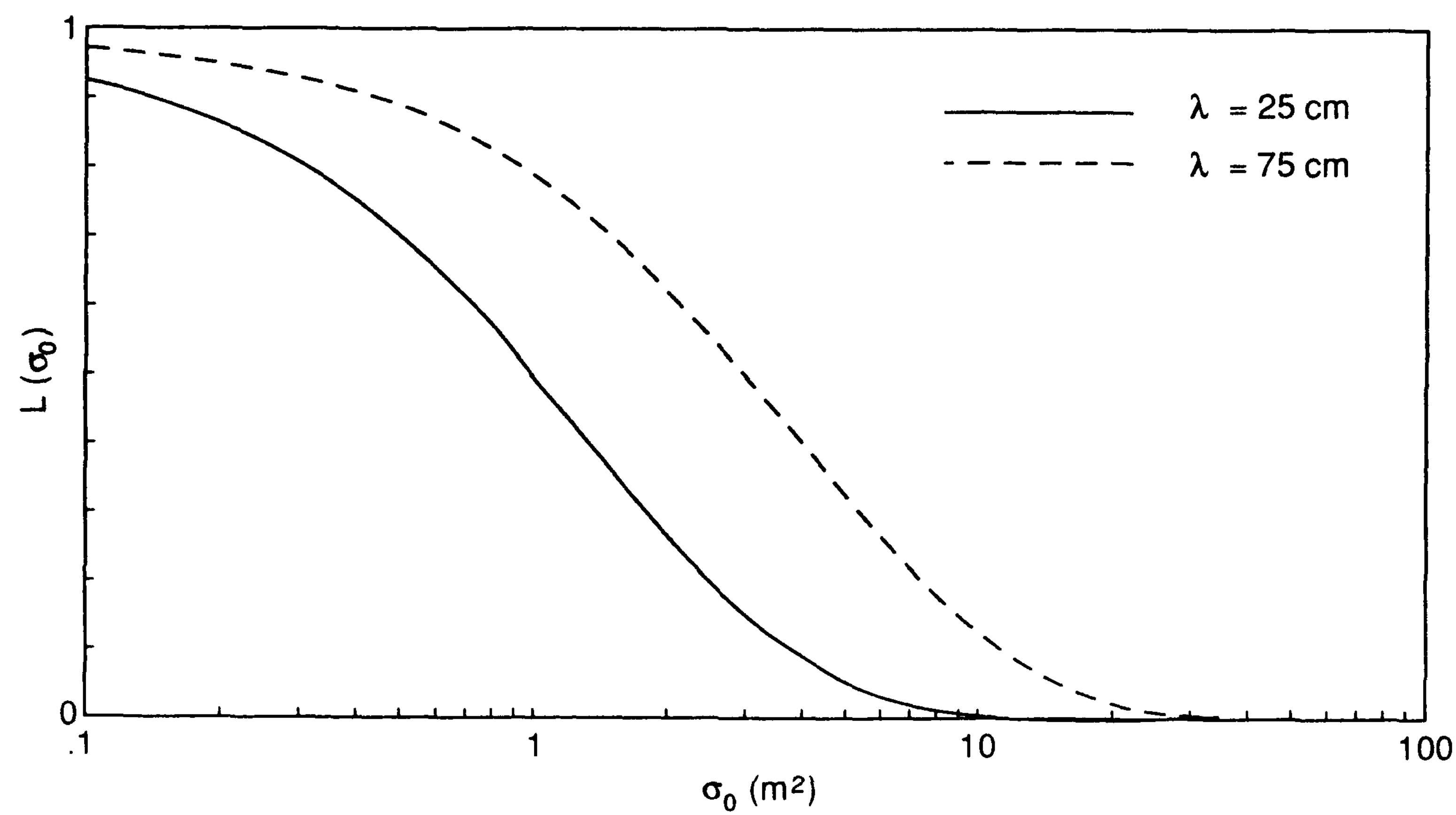

Figure 3d. The Probability That a Flock Has a Mean Radar Cross Section Equal to or Greater Than a Specified Value, σ_0. White Fronted Goose.

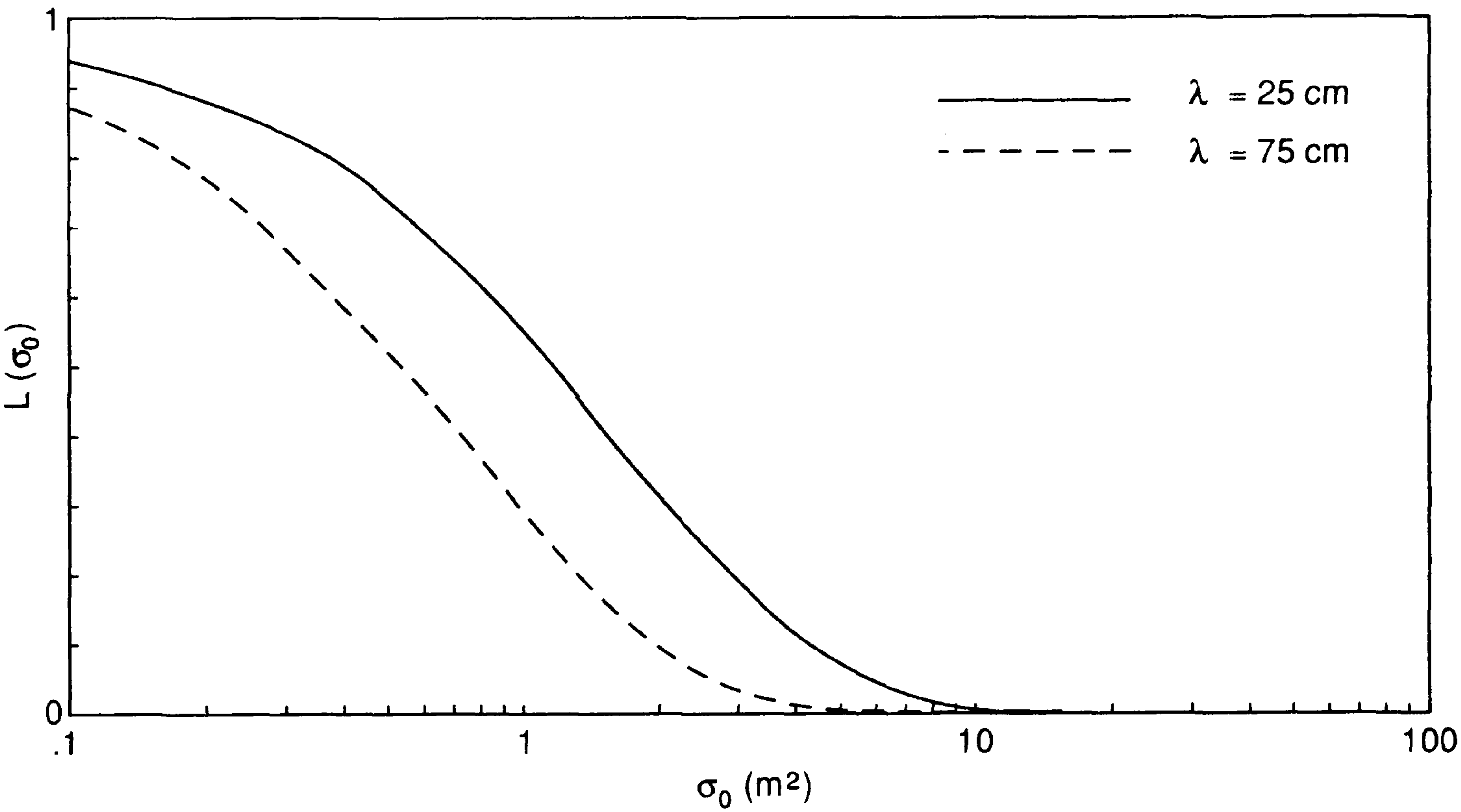

Figure 3e. The Probability That a Flock Has a Mean Radar Cross Section Equal to or Greater Than a Specified Value, σ_0. Oldsquaw.

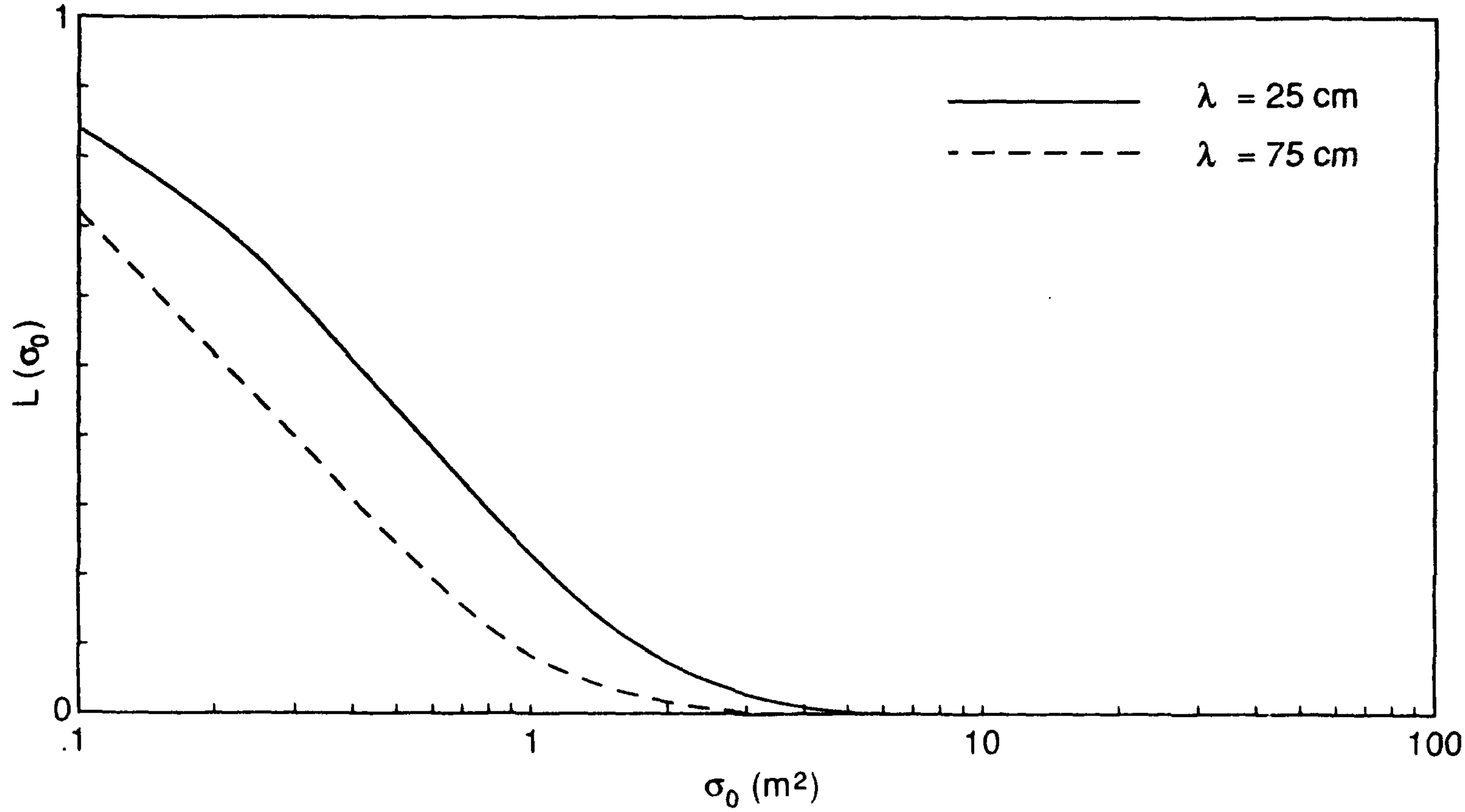

Figure 3f. The Probability That a Flock Has a Mean Radar Cross Section Equal to or Greater Than a Specified Value, σ_0. Pintail.

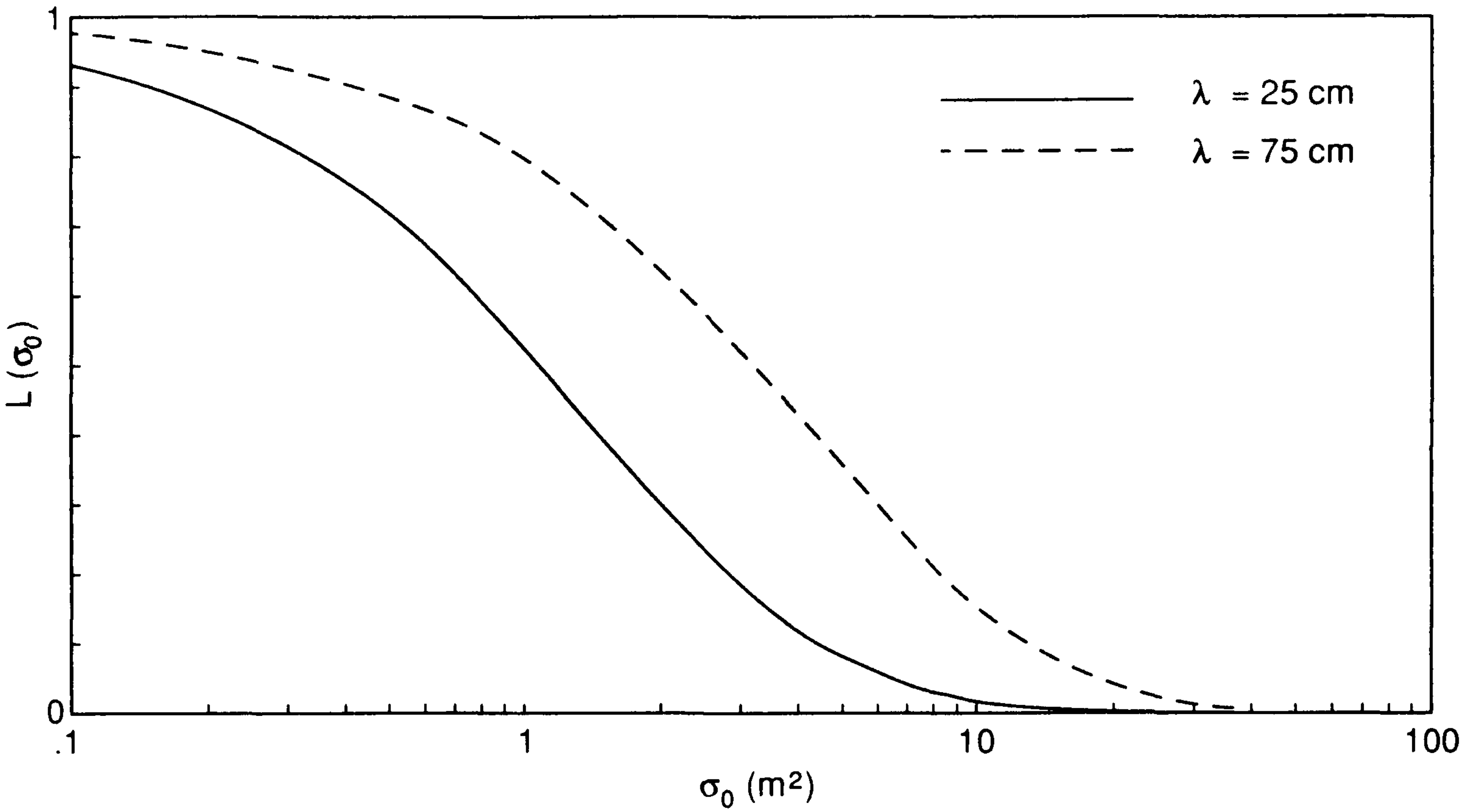

Figure 3g. The Probability That a Flock Has a Mean Radar Cross Section Equal to or Greater Than a Specified Value, σ_0. Whistling Swan.

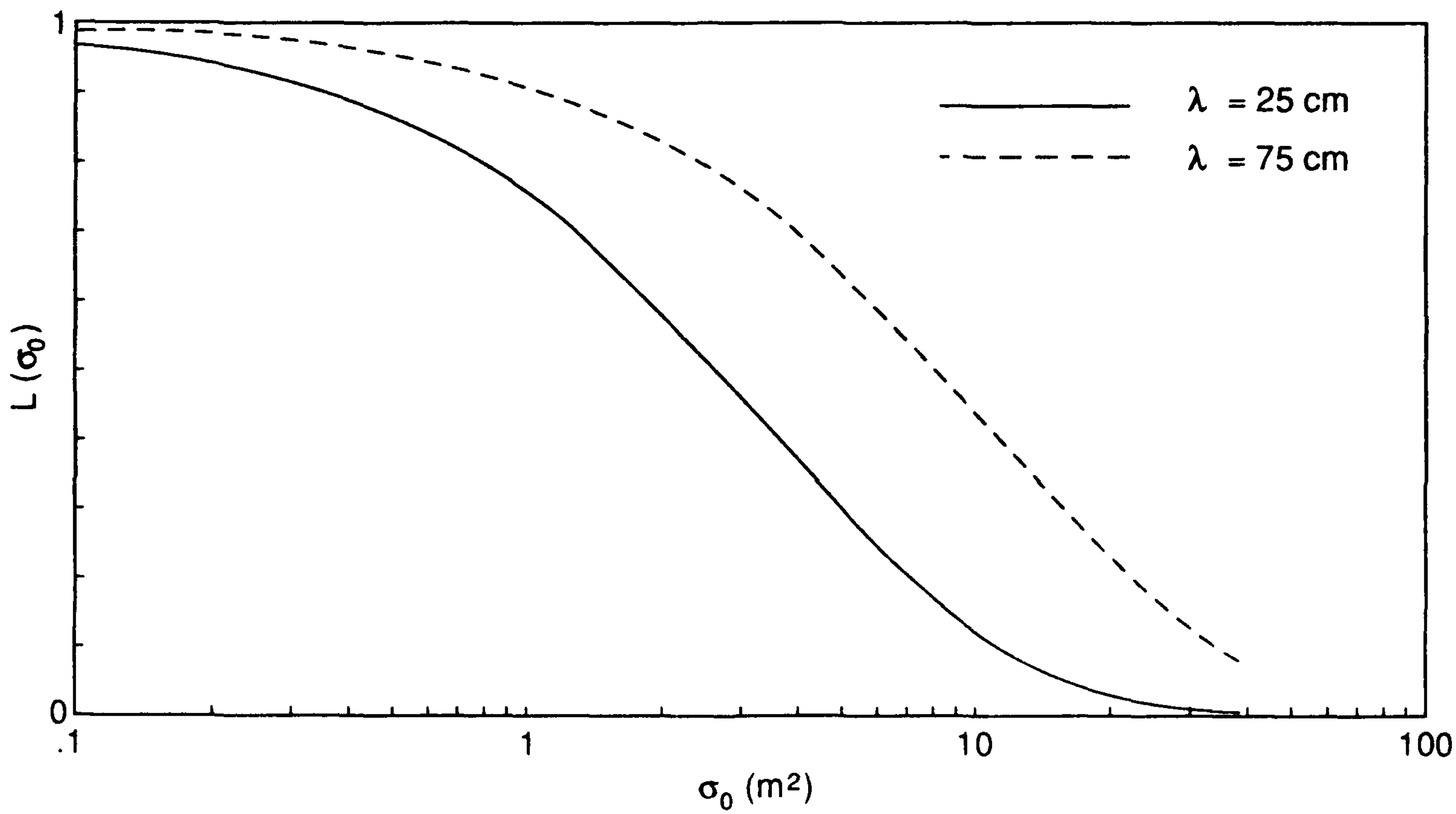

Figure 3h. The Probability That a Flock Has a Mean Radar Cross Section Equal to or Greater Than a Specified Value, σ_0. Greater Snow Goose.

4. PROBABILITY THAT AT LEAST M OUT OF Q FLOCKS OBSERVED HAVE A SPECIFIED RADAR CROSS SECTION

At times, a number of flocks of birds may be detected, and they will most likely have a wide variety of radar cross sections. However, only some of the flocks will have a radar cross section large enough to be considered significant.

If the number of flocks Q, of a species of birds are observed, then what is the probability that there will be M or more flocks with a cross section greater than an arbitrary value of the flock's mean RCS σ_0 ? The viewing of the flocks can be looked upon in a probabilistic fashion by considering Q as the number of trials, M, with the right value of RCS, as a success, and only two outcomes being possible, a success or a failure. Each event is random and independent. This condition results in a binomial distribution[4,5]. The probability of having M successes out of Q observations would then be the binomial distribution times the probability of observing Q flocks. The probability of a binomial distribution is given by :

$$b(M,Q,L) = \frac{Q!}{M!\,(Q-M)!} L^M (1-L)^{Q-M} \tag{27}$$

where M is the number of successes, Q is the number of independent occurrences , and L is the probability that a single flock will have a cross section equal to or greater than a specified quantity. The probability of getting M or more successes is:

$$P(M \mid Q;L) = B(M,Q,L) \tag{28}$$

where

$$B(M,Q,L) = \sum_{M'=M}^{Q} b(M',Q,L)\,. \tag{29}$$

We now include the probability function, $f(Q)\,\Delta Q$, for observing Q flocks, where Q is the number of flocks on the radar screen. The probability of seeing specifically Q flocks, and M or more flocks having a $\sigma \geq \sigma_0$ is:

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5 Miller, I. and Freund, J.E. (1965) *Probability and Statistics for Engineers*, Prentice-Hall, Inc., Englewood Cliffs, N.J.

$$P(M \mid Q;L)p(Q) = \left[\sum_{M'=M}^{Q} b(M',Q,L) \right] f(Q)\,\Delta Q \tag{30}$$

with the condition that $Q \geq M$. The probability of M or more successes for up to Q_1 observed flocks is:

$$P(M) = \sum_{Q=M}^{Q_1} P(M,Q), \tag{31}$$

or,

$$P(M) = \sum_{Q=M}^{Q_1} \left[\sum_{M'=M}^{Q} b(M',Q,L) \right] f(Q)\,\Delta Q\,. \tag{32}$$

To obtain the probability of their being M or more successes for any number of flocks seen, we let Q_1 go to infinity. For an arbitrary value of M, and expressing the probability in integral form, we get

$$P(M) = \int_{M}^{\infty} \left[\sum_{M'=M}^{Q} b(M',Q,L) \right] f(Q)\,dQ\,. \tag{33}$$

We must point out that we have assumed that L is a constant, that is, L does not vary with Q. If the number of birds is quite small, and therefore, there is a correspondingly small number of flocks, there should come a point where L is affected. However, for our purposes, our assumption regarding L seems reasonable.

Now we address the density function f(Q). To obtain f(Q), we need an expression for Q. Q equals the number of birds per radar coverage, $N_o f(x)\Delta x$, [where f(x) is given by Eq. (3)], divided by the number of birds per flock, y. The ensuing mathematics can be made more manageable by introducing a simplification[4] , namely the use of a single value for the normal distribution, f(x). In our analysis, we will take the peak value of the number of birds per radar coverage, which we designate as A. Then $Q = A/y$, where A is determined from Eq. (6). From Papoulis[6], we obtain the probability density f(Q):

$$f(Q) = \frac{A}{Q^2} f(y)\Big|_{y=A/Q} , \tag{34}$$

and using the expression for f(y) from Eq. (11),

$$f(Q) = \frac{1}{Q\beta\sqrt{2\pi}} e^{-(1/2)\left\{[\ln(A/Q)-\alpha]/\beta\right\}^2} . \tag{35}$$

Substituting Eq. (35) into Eq. (33), we obtain

$$P = \int_M^{\infty} \left[\sum_M^Q b(M,Q,L)\right] \frac{1}{Q\beta\sqrt{2\pi}} e^{-(1/2)\left\{[\ln(A/Q)-\alpha]/\beta\right\}^2} dQ . \tag{36}$$

P is a function of M, with L as a parameter. Evaluating P is a formidable task. The calculations are time consuming even for a computer. Therefore, it is, at some point, advantageous to use the normal distribution approximation to the binomial distribution. The larger Q is, the greater the accuracy of the approximation. To use the approximation, Q should be greater than 5/min (L,1-L). So in our computations, to evaluate P, the binomial distribution was used for the lower values of Q, and the normal distribution approximation was used for the higher values of Q. The normal distribution was put in analytical form by using a polynomial approximation method[7]. The program was also written in LISP lanquage which is faster, more sophisticated, and offers more control for plotting[8]. The results are shown in Figures 4A1 to 4A22, and 4B1 to 4B13 and are applicable to the peak span of the migration period of each species of bird. There are a few cases in spring migration that are not

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[6] Papoulis, A. (1965) *Probability, Random Variables, and Stochastic Processors*, McGraw-Hill Book Company, New York, N.Y.

[7] Hewlett-Packard Co. (1975) Hewlett-Packard HP-25 Applications programs, 00025-90011 Revised Edition 7/76.

[8] Computer program. *Bird-Clutter Program Framework LISP code*, written by Captain Terry O'Donnell, RADC/FE[illegible] Hanscom AFB, MA.

shown since they would duplicate the results of the fall migration. They are as follows: the Oldsquaw and Pintail in North Alaska, the Oldsquaw, Pintail, and Whistling Swan in Western Canada, the Oldsquaw in Central Canada, and the Oldsquaw, Whistling Swan, and Greater Snow Goose in Eastern Canada. The curves are shown drawn through the calculated values continuously for the sake of clarity. In reality, there are only data points at the integers since there are no fractions of a flock.

The plots depict probabilities for three cases of a flock's radar cross section; σ_0 equal to 1 m^2, 0.1 m^2, and 0.01 m^2. The results seem reasonable. The curves show that the chance of having flocks of lower cross section is greater than having flocks of higher cross section, and the chance increases quickly as an approximate limiting value of 0.01 m^2 is approached. The main reason for this behavior is that, for a given number of birds, there would be a greater number of flocks of smaller rather than larger size occurring within the same probability range. Because of this greater number of flocks, there is a greater chance of getting a specified quantity of them with the smaller cross section. The flock's size together with the bird's cross section leads to a large number of flocks with a low RCS till a point of saturation is reached. An RCS of 0.01 m^2 is just about saturation since there are not many flocks with less than that value.

We may also notice that, for a given probability, the number of flocks M increases within generally the same order of magnitude as the increase of the number of birds on the radar screen. Further insight may be gained from the curves by looking at the difference between the σ_0 = 1 m^2 and σ_0 =0 .1 m^2 curves for the Pintail. The usual flock density of the Pintail is 20 to 70 birds per flock, which means its usual flock mean RCS is between 0.27 m^2 and 0.95 m^2. That means there would be a high chance of the Pintail's flock RCS being 0.1 m^2 or greater, and a much lower chance of having 1 m^2 or greater. The usual flock size has a strong influence on the variable M. The Eider's value of M, for a given probability, is much higher than, for instance, the Lesser Snow Goose's equivalent value. This is because its flock size is smaller while still maintaining a high enough RCS, and so there would be a greater number of flocks satisfying the necessary criteria.

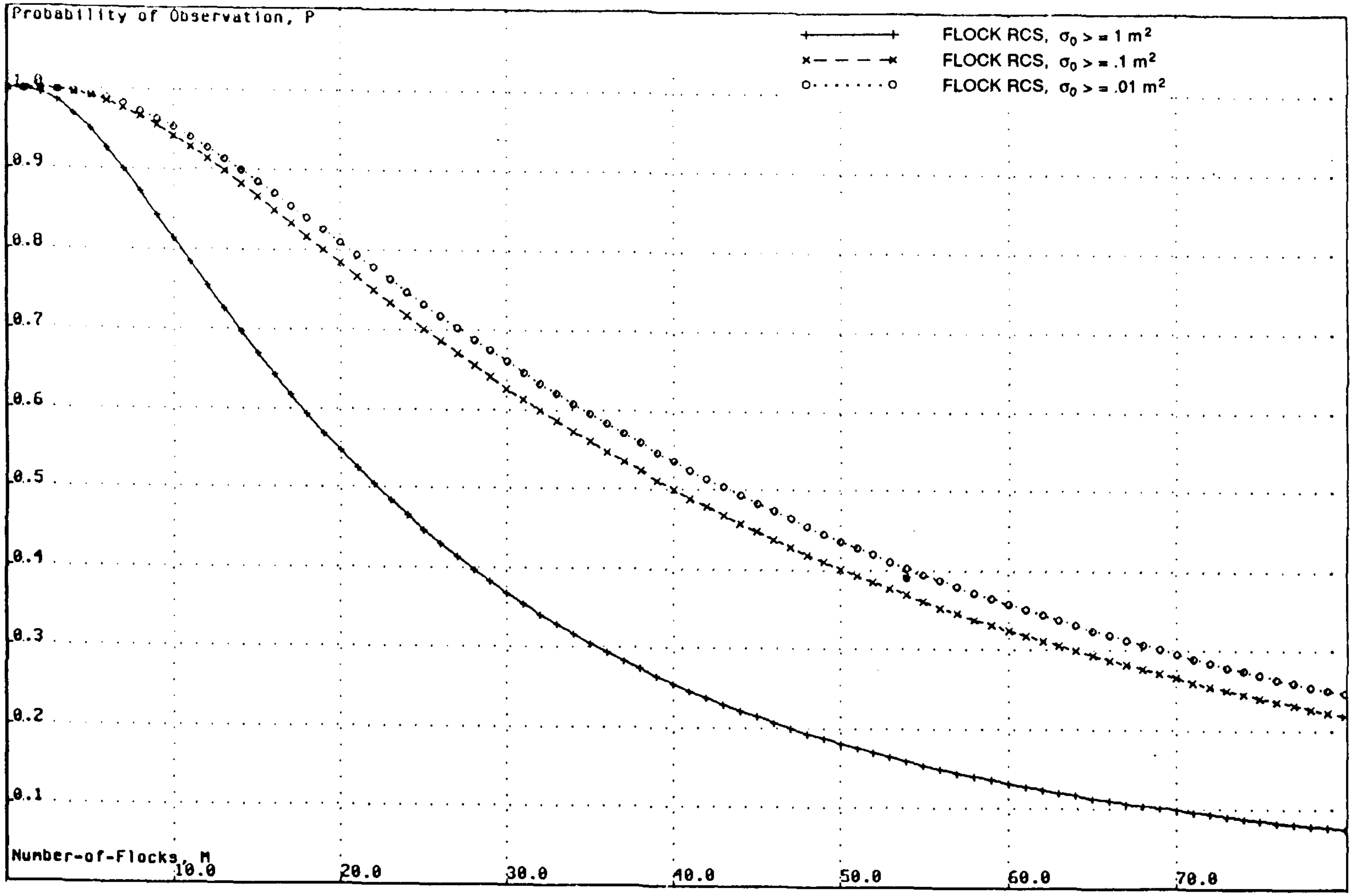

Figure 4a1. Probability of Observing, During Peak Migration, at Least M Flocks With a Mean Radar Cross Section Equal to or Greater Than a Specified Value, σ_0. North Alaska ---- Fall ---- Eider.

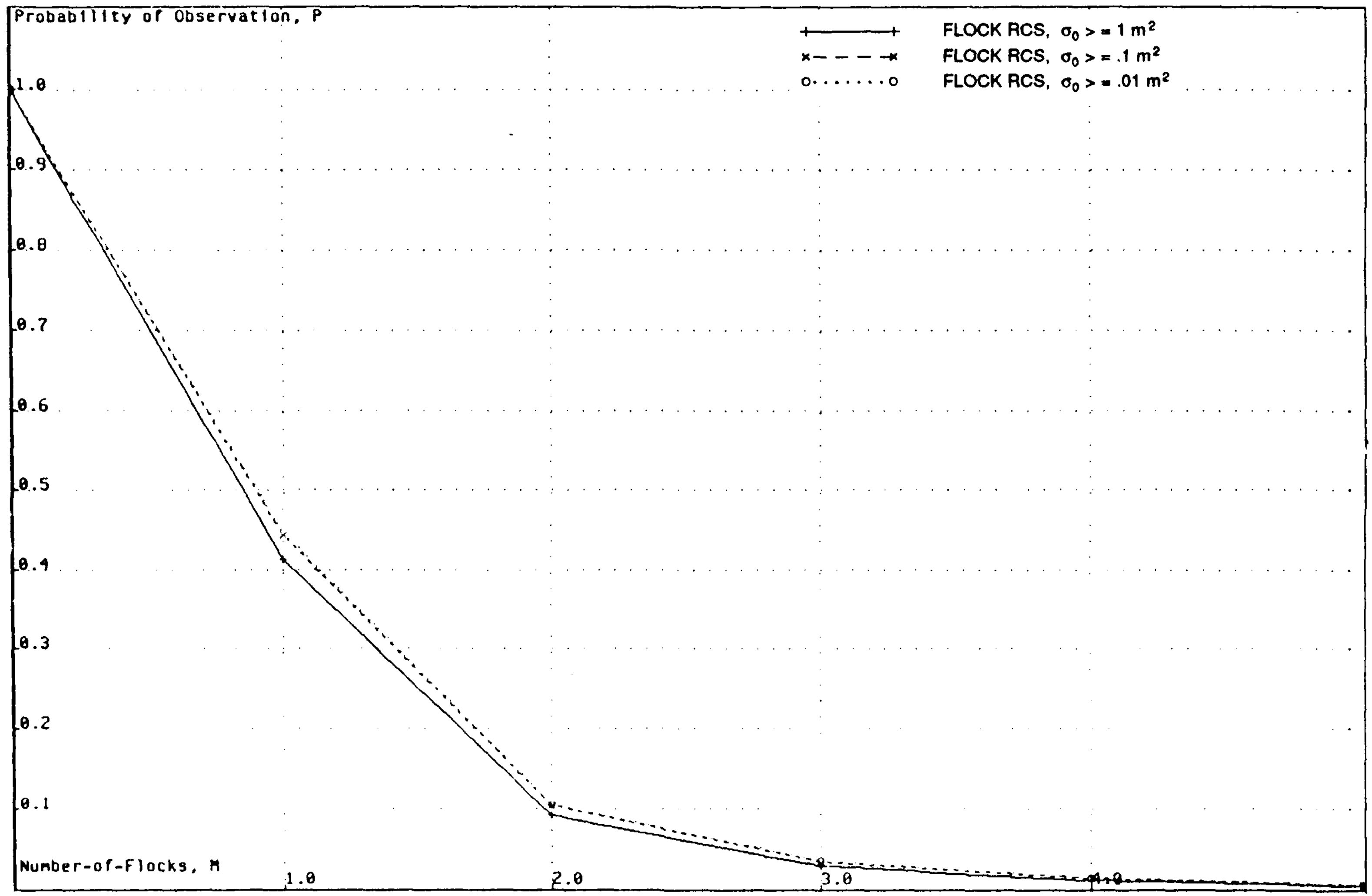

Figure 4a2. Probability of Observing, During Peak Migration, at Least M Flocks With a Mean Radar Cross Section Equal to or Greater Than a Specified Value, σ_0. North Alaska ---- Fall ---- Brant.

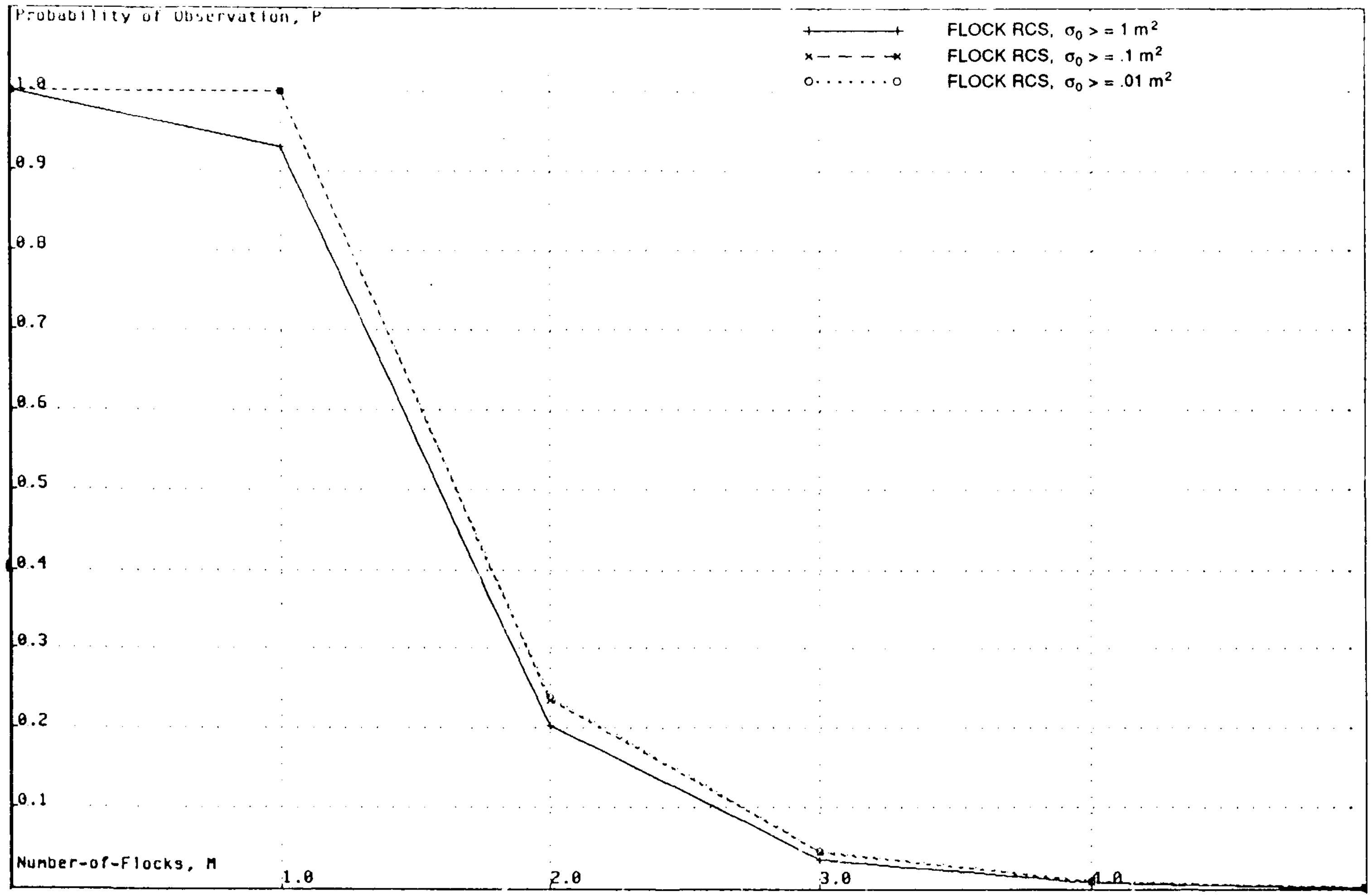

Figure 4a3. Probability of Observing, During Peak Migration, at Least M Flocks With a Mean Radar Cross Section Equal to or Greater Than a Specified Value, σ_0. North Alaska ---- Fall ---- Lesser Snow Goose.

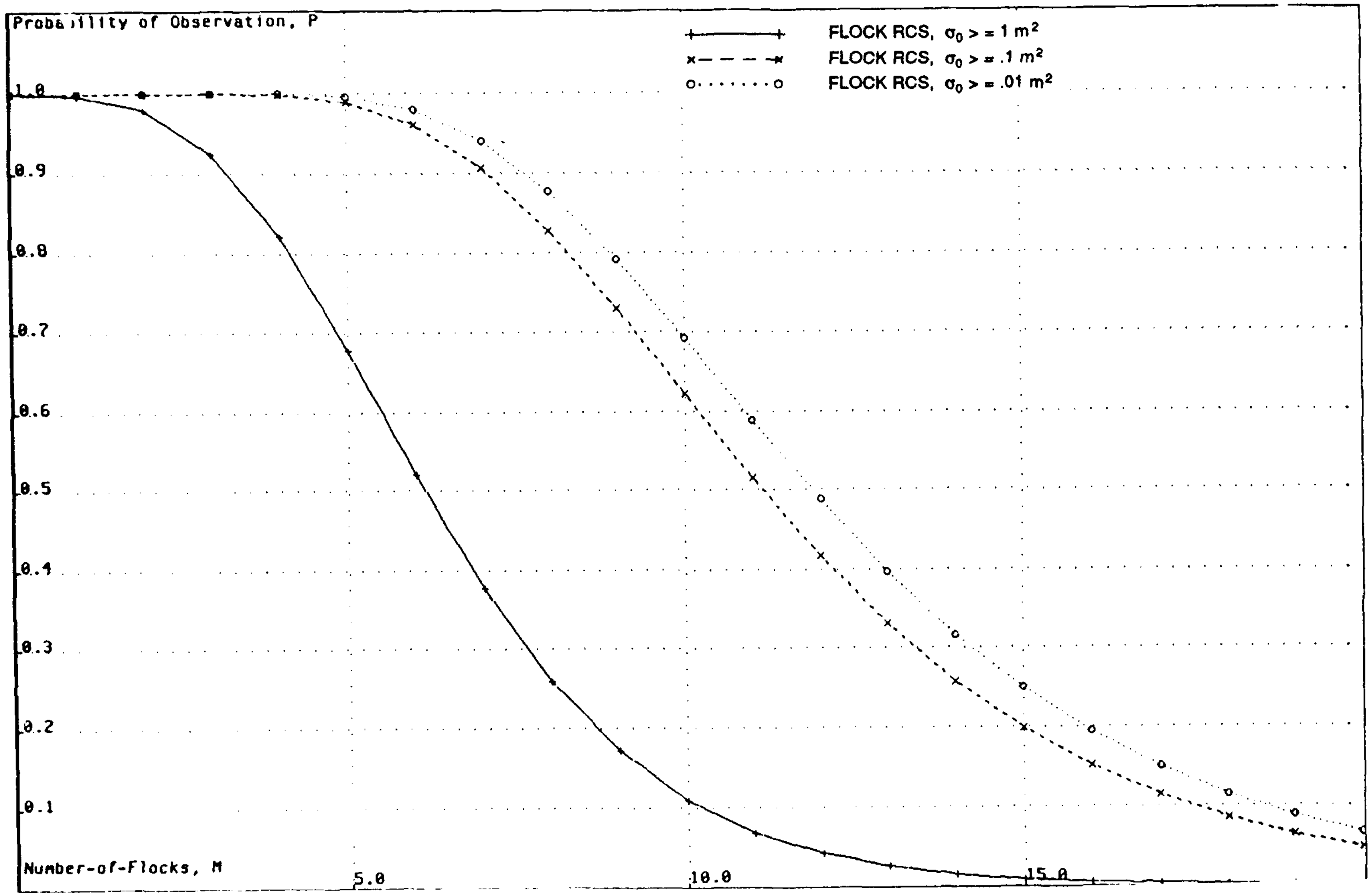

Figure 4a4. Probability of Observing, During Peak Migration, at Least M Flocks With a Mean Radar Cross Section Equal to or Greater Than a Specified Value, σ_0. North Alaska ---- Fall ---- White Fronted Goose.

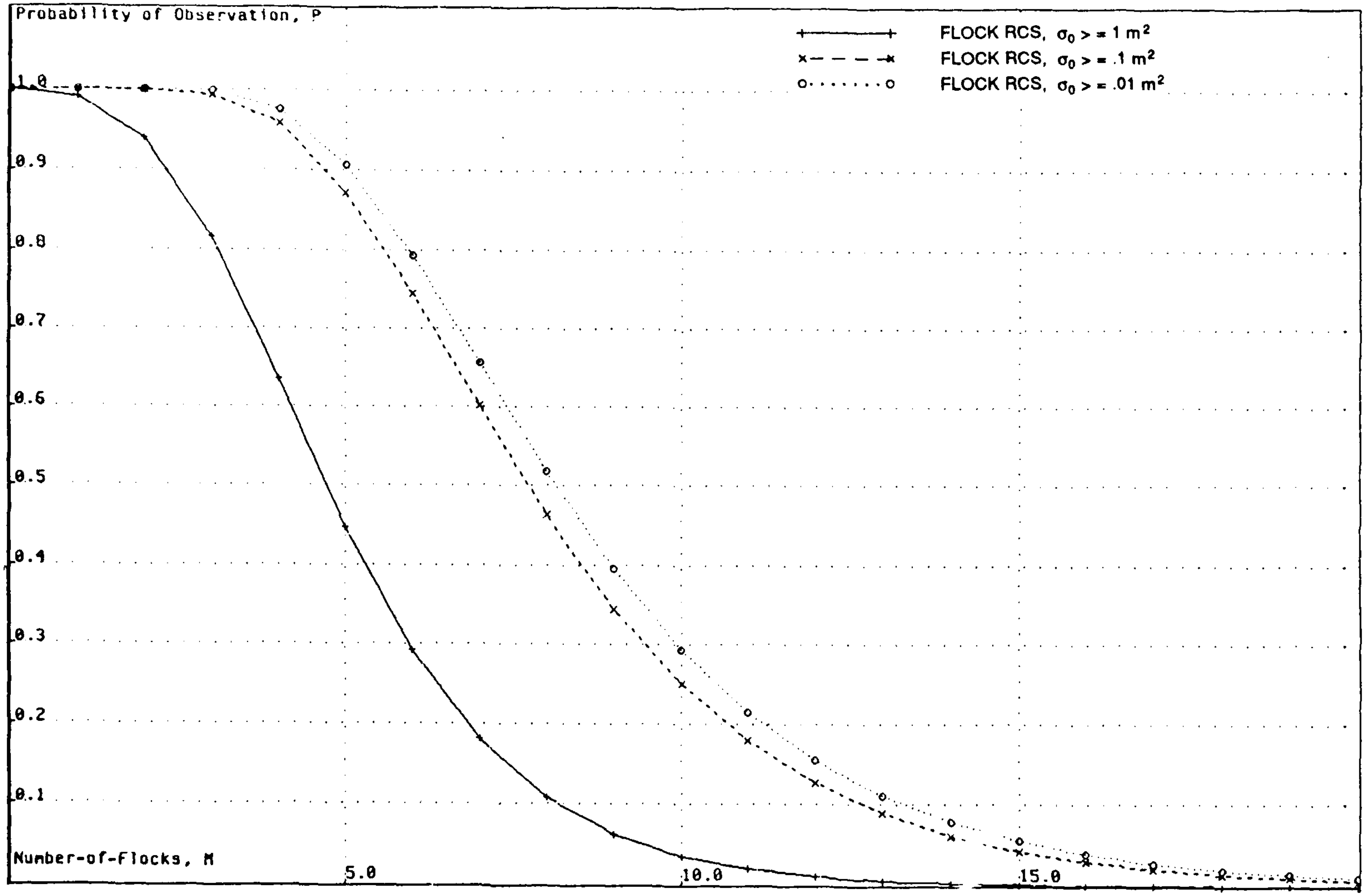

Figure 4a5. Probability of Observing, During Peak Migration, at Least M Flocks With a Mean Radar Cross Section Equal to or Greater Than a Specified Value, σ_0. North Alaska ---- Fall ---- Oldsquaw.

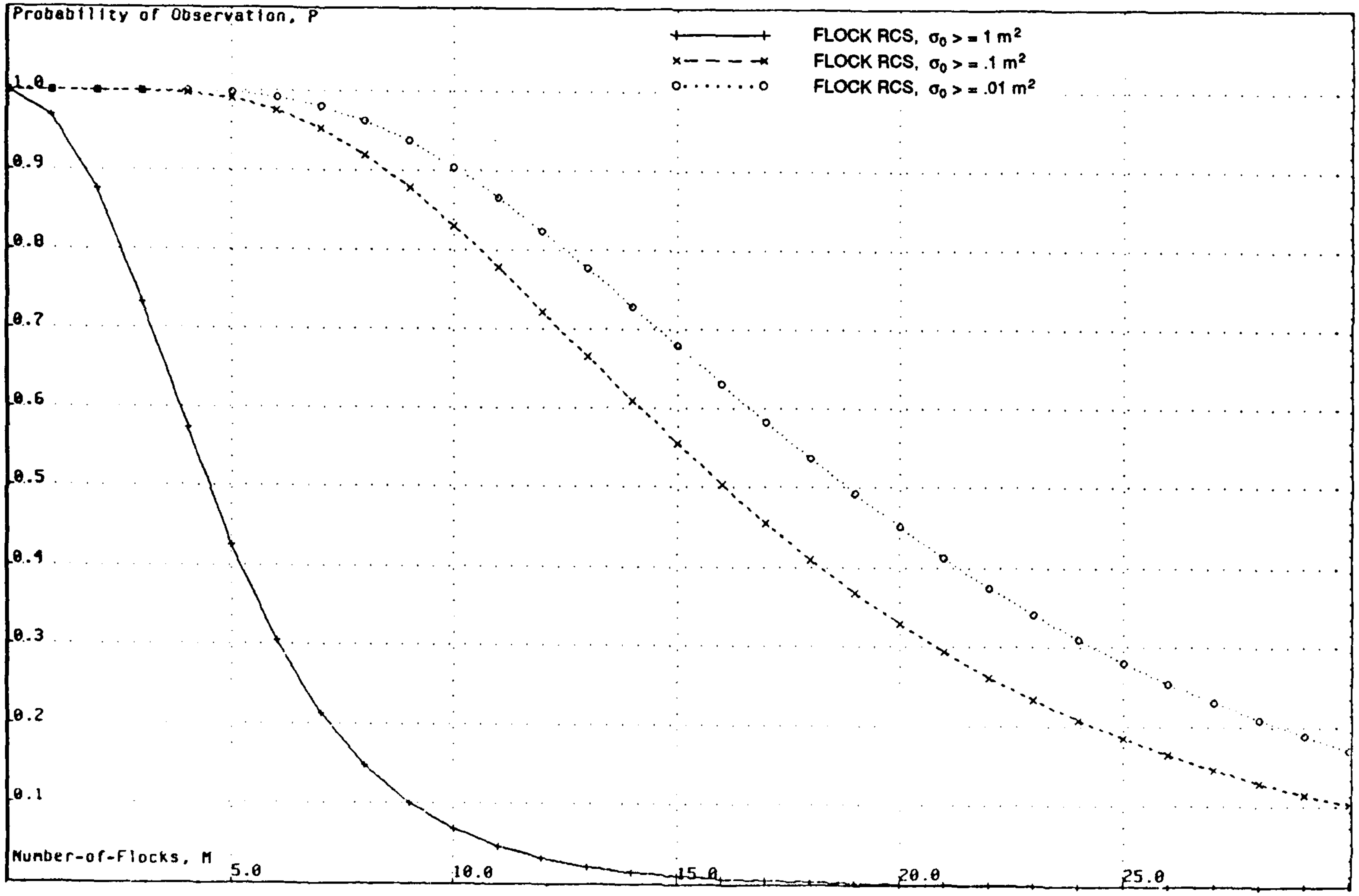

Figure 4a6. Probability of Observing, During Peak Migration, at Least M Flocks With a Mean Radar Cross Section Equal to or Greater Than a Specified Value, σ_0. North Alaska ---- Fall ---- Pintail.

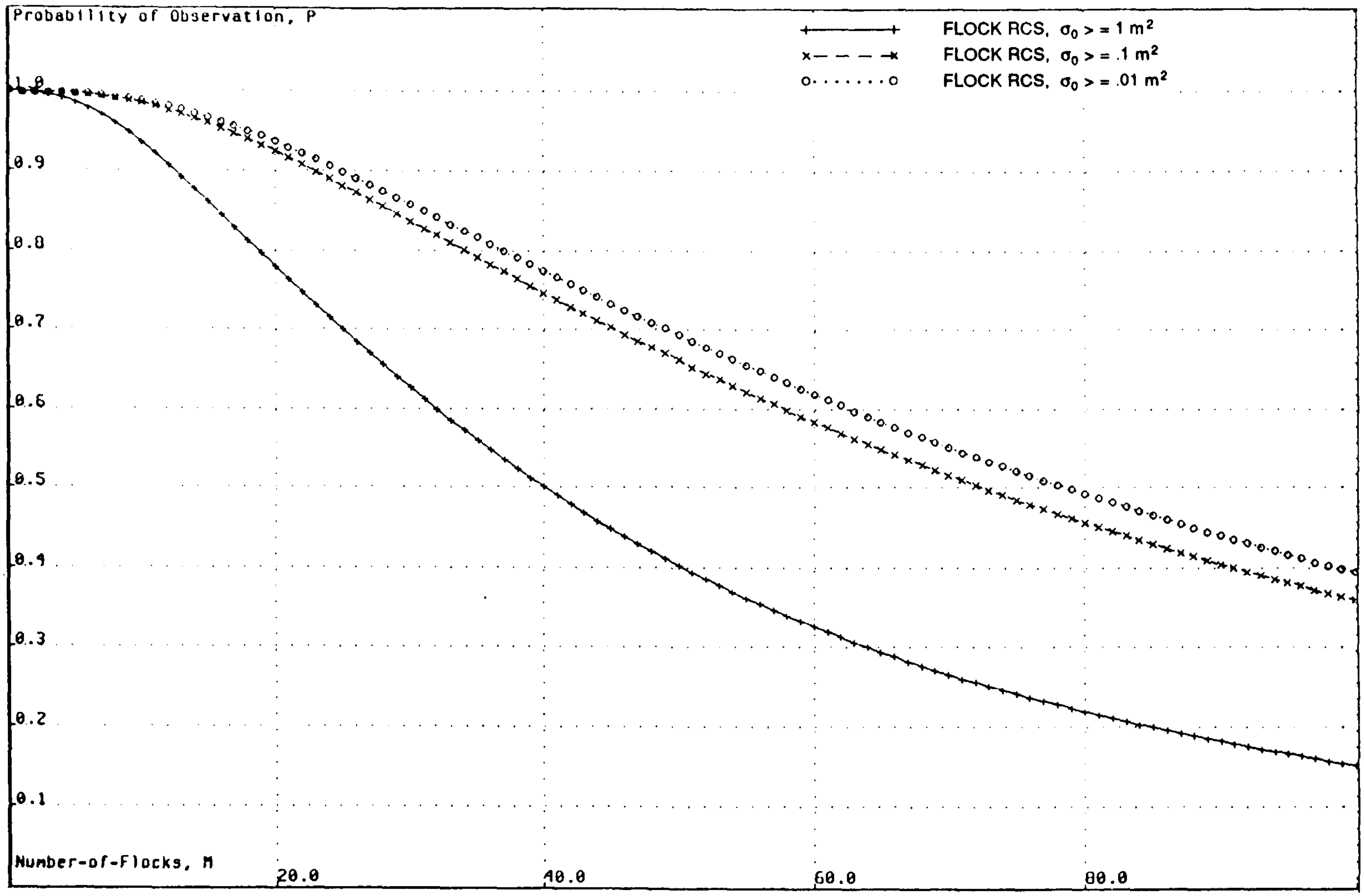

Figure 4a7. Probability of Observing, During Peak Migration, at Least M Flocks With a Mean Radar Cross Section Equal to or Greater Than a Specified Value, σ_0. Western Canada ---- Fall ---- Eider.

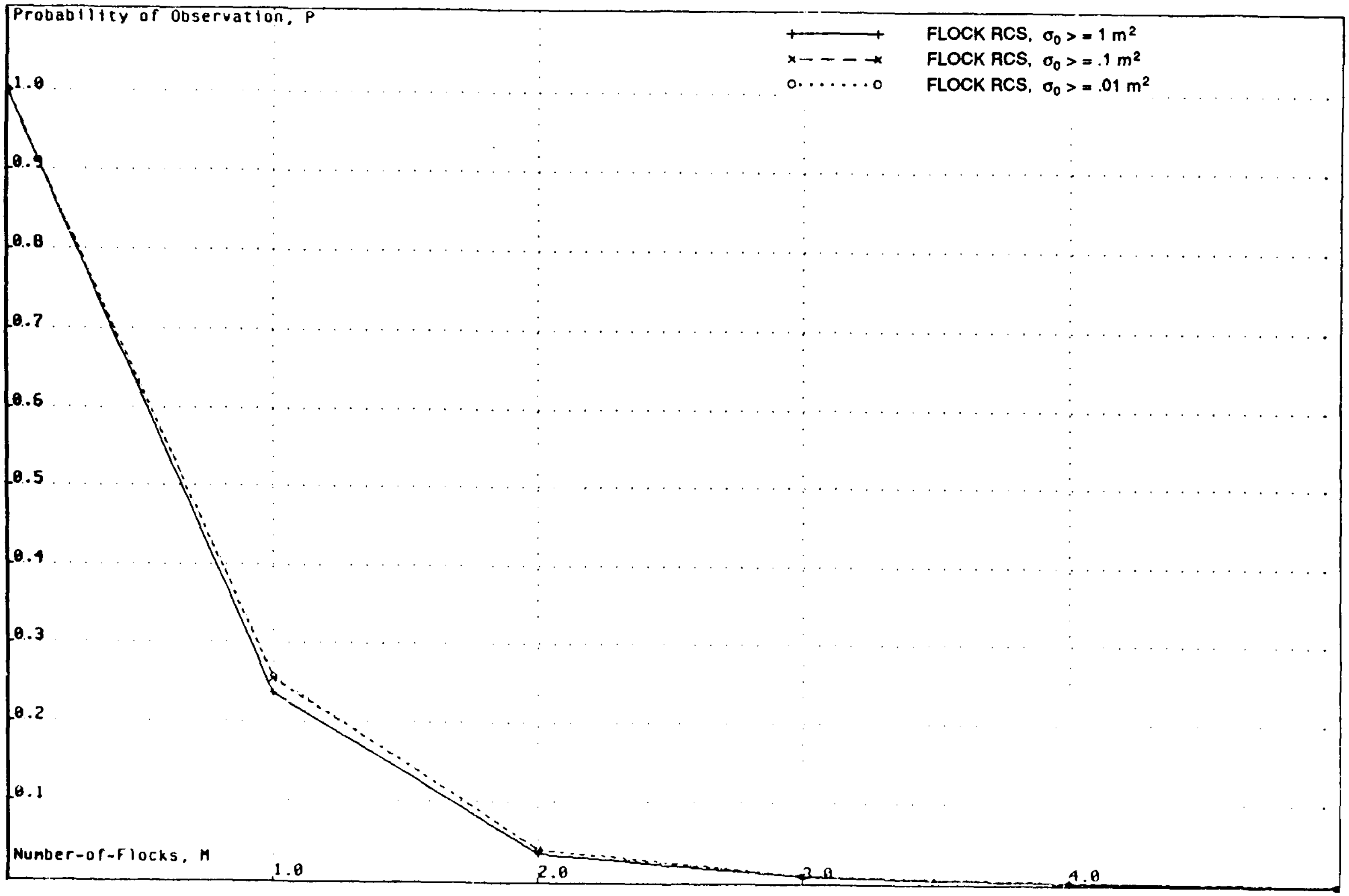

Figure 4a8. Probability of Observing, During Peak Migration, at Least M Flocks With a Mean Radar Cross Section Equal to or Greater Than a Specified Value, σ_0. Western Canada ---- Fall ---- Brant.

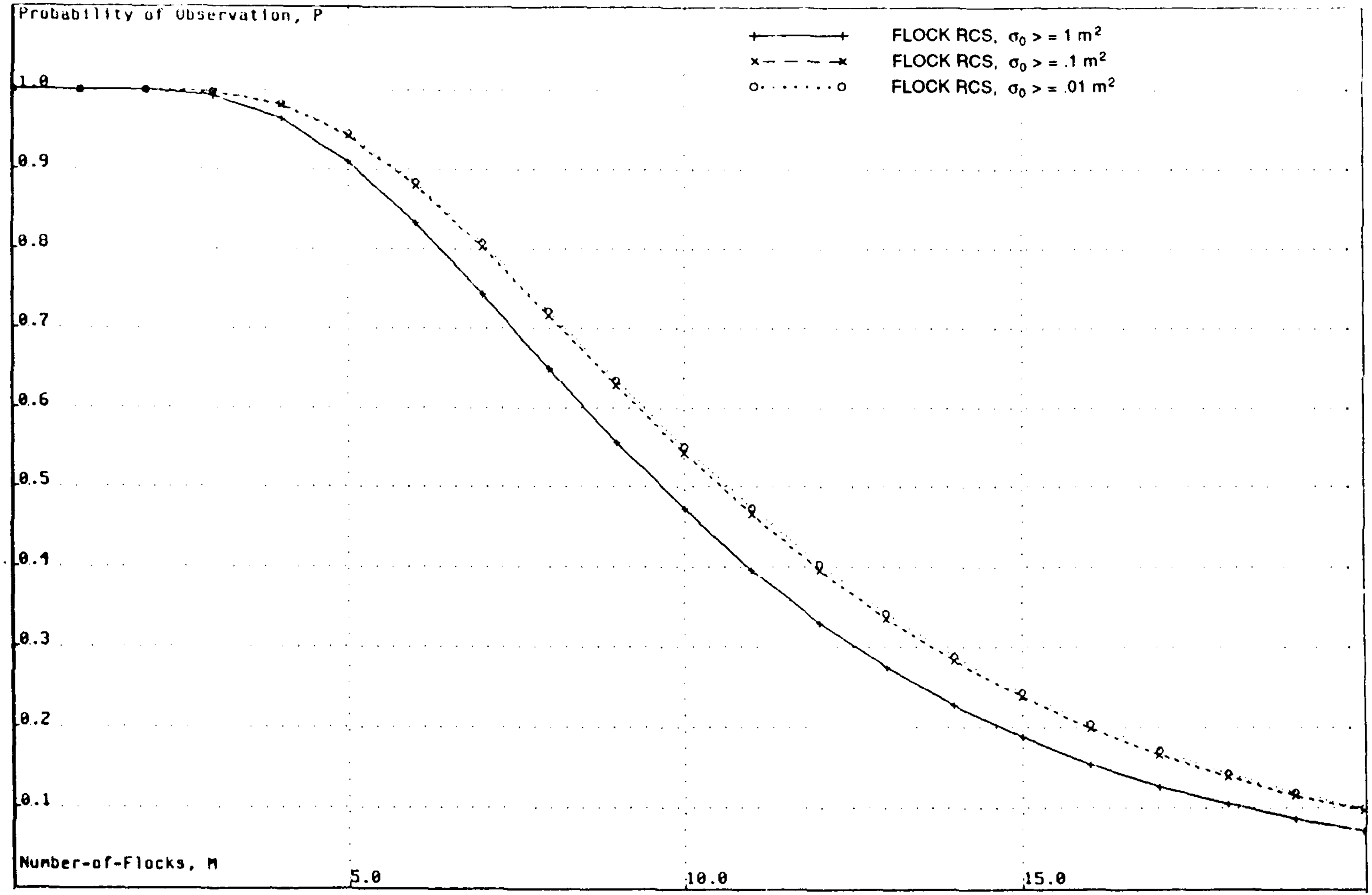

Figure 4a9. Probability of Observing, During Peak Migration, at Least M Flocks With a Mean Radar Cross Section Equal to or Greater Than a Specified Value, σ_0. Western Canada ---- Fall ---- Lesser Snow Goose.

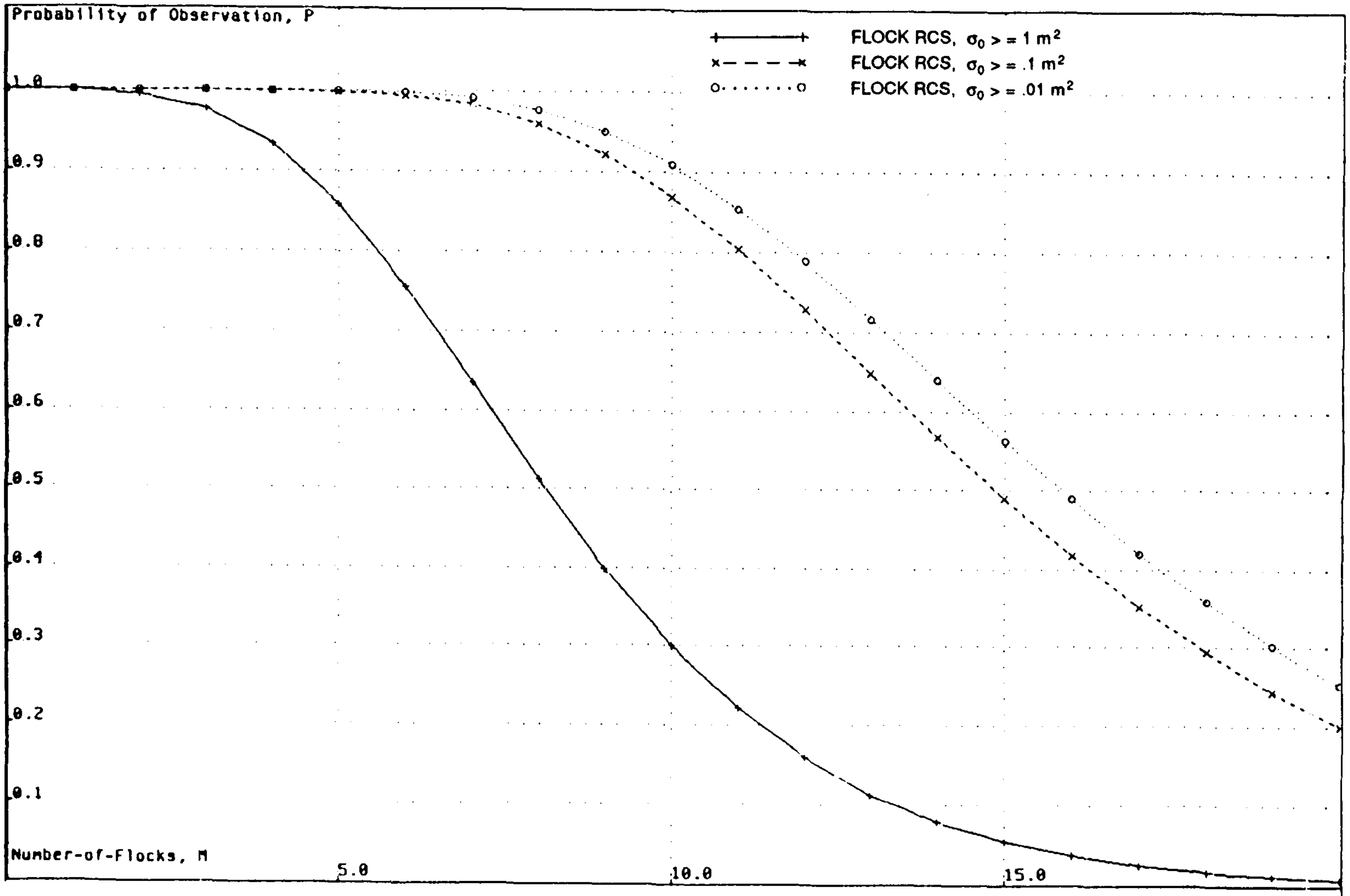

Figure 4a10. Probability of Observing, During Peak Migration, at Least M Flocks With a Mean Radar Cross Section Equal to or Greater Than a Specified Value, σ_0. Western Canada ---- Fall ---- White Fronted Goose.

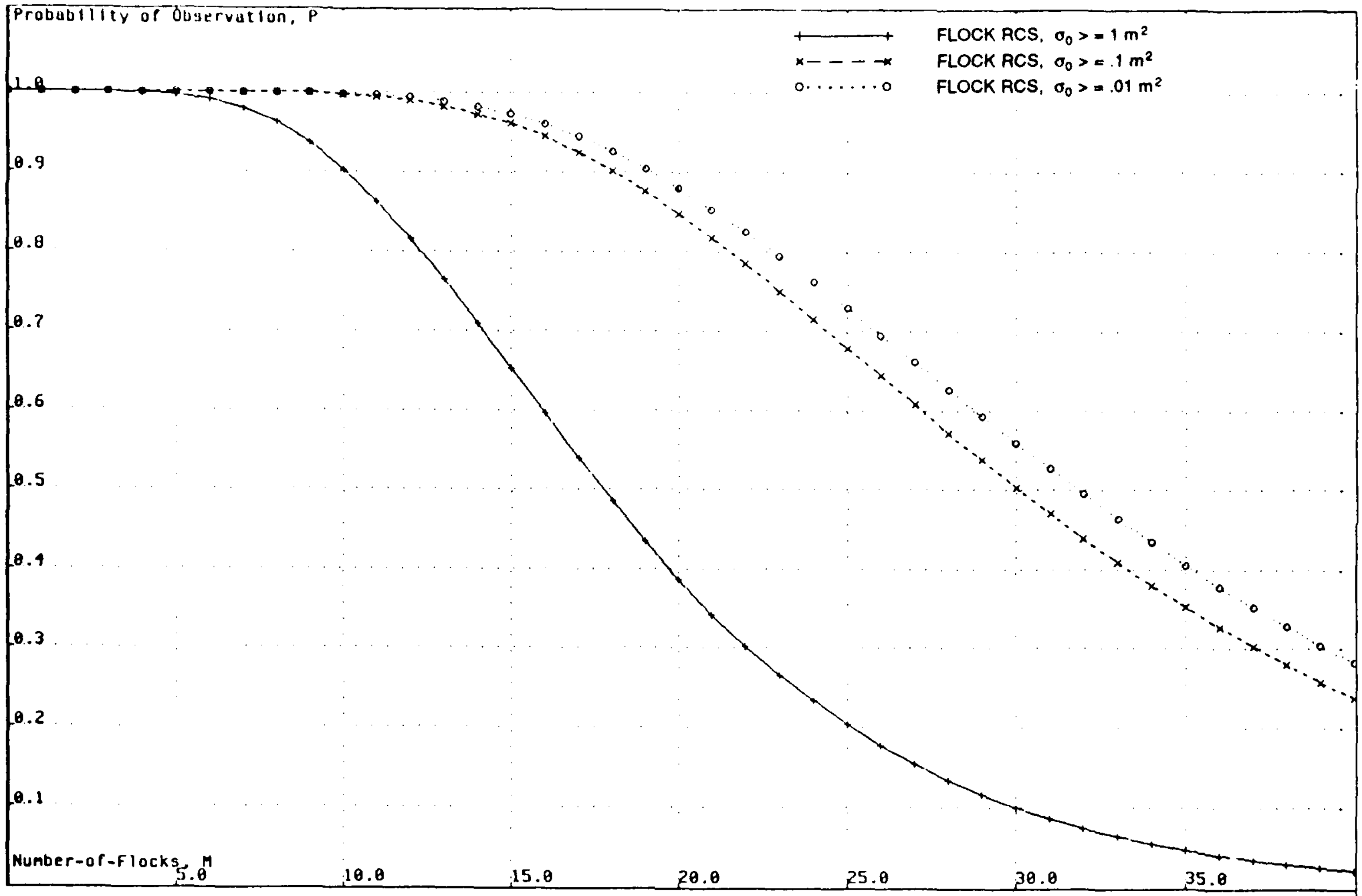

Figure 4a11. Probability of Observing, During Peak Migration, at Least M Flocks With a Mean Radar Cross Section Equal to or Greater Than a Specified Value, σ_0. Western Canada ---- Fall ---- Oldsquaw.

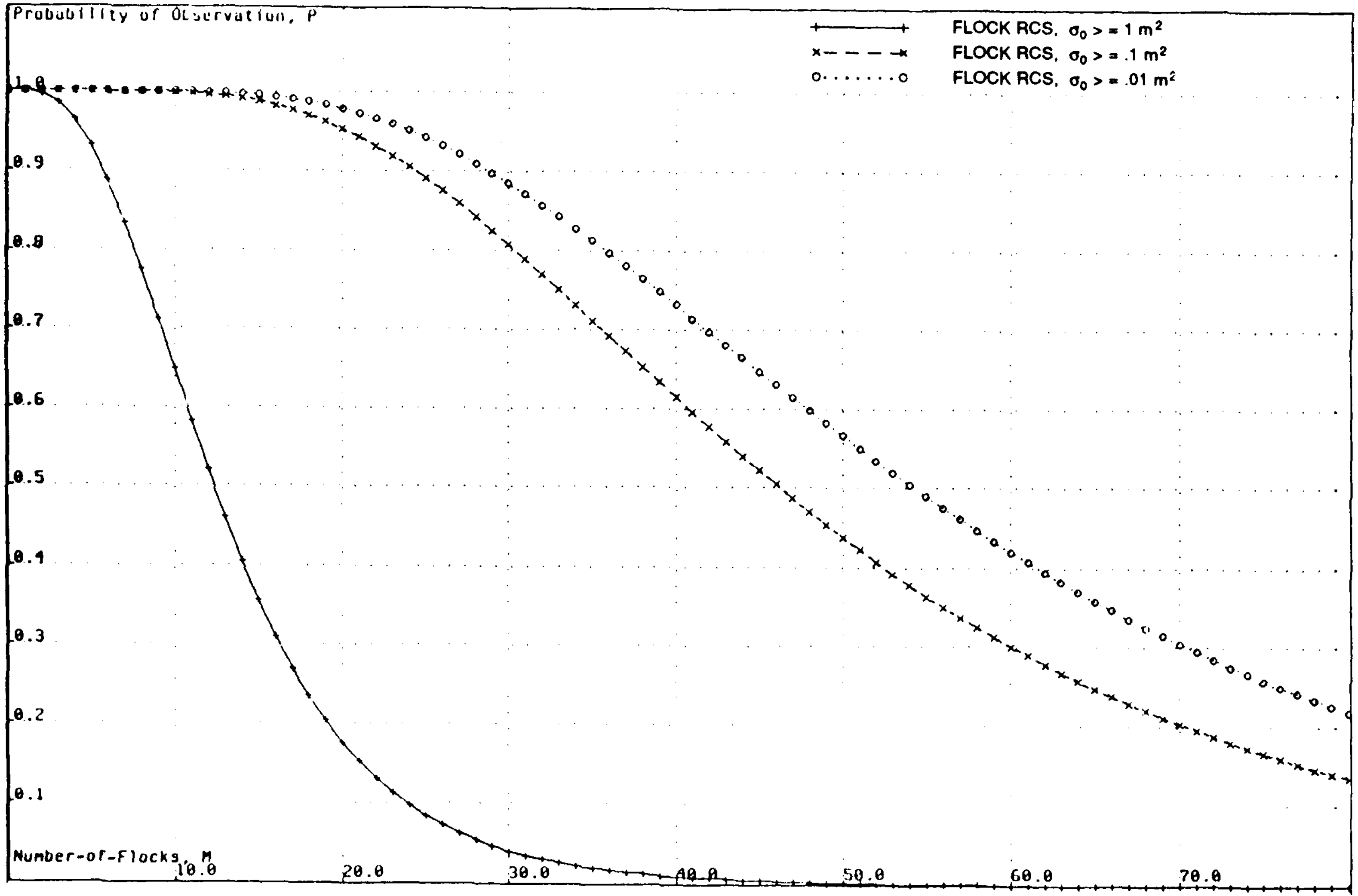

Figure 4a12. Probability of Observing, During Peak Migration, at Least M Flocks With a Mean Radar Cross Section Equal to or Greater Than a Specified Value, σ_0. Western Canada ---- Fall ---- Pintail.

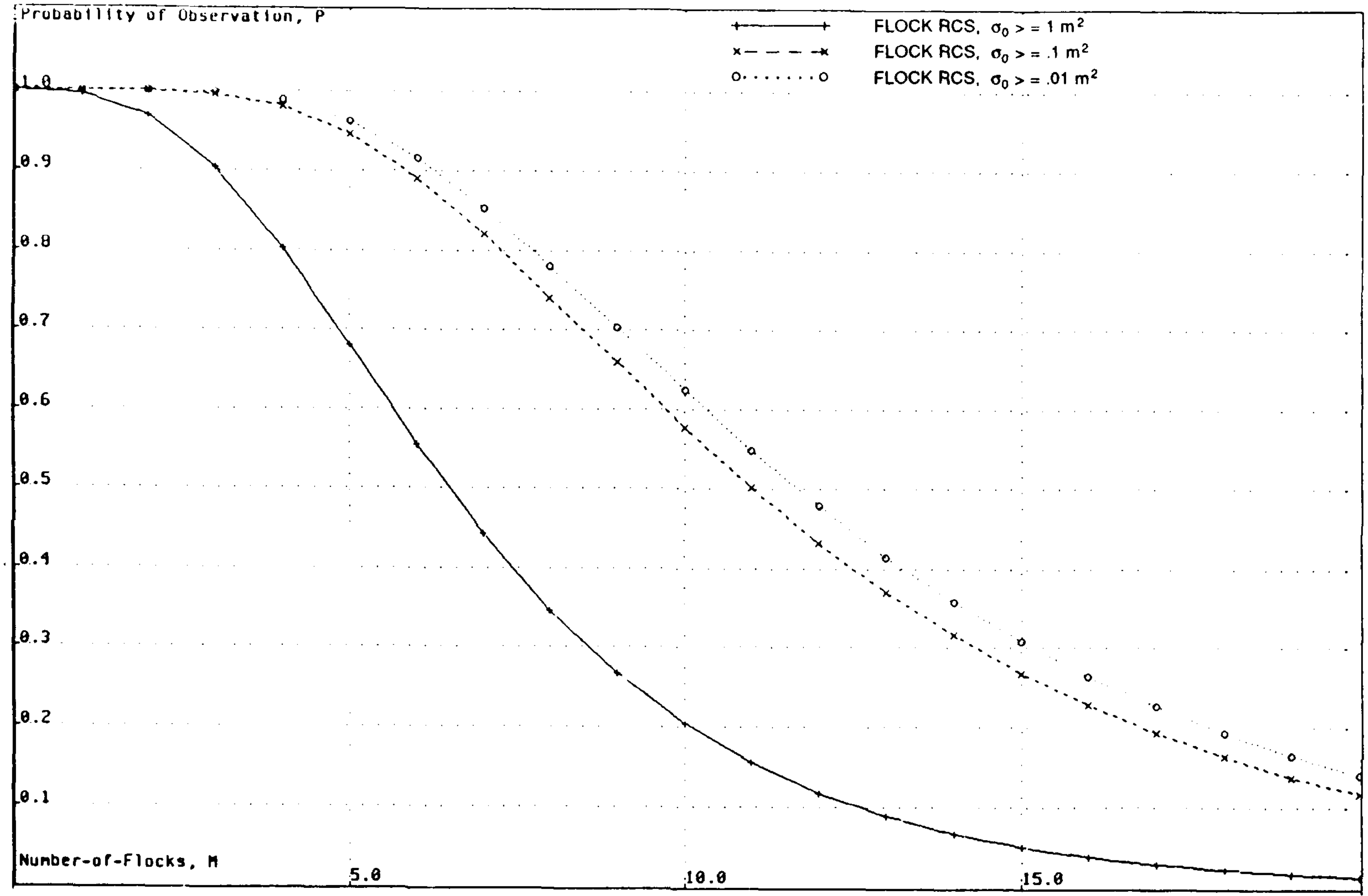

Figure 4a13. Probability of Observing, During Peak Migration, at Least M Flocks With a Mean Radar Cross Section Equal to or Greater Than a Specified Value, σ_0. Western Canada ---- Fall ---- Whistling Swan.

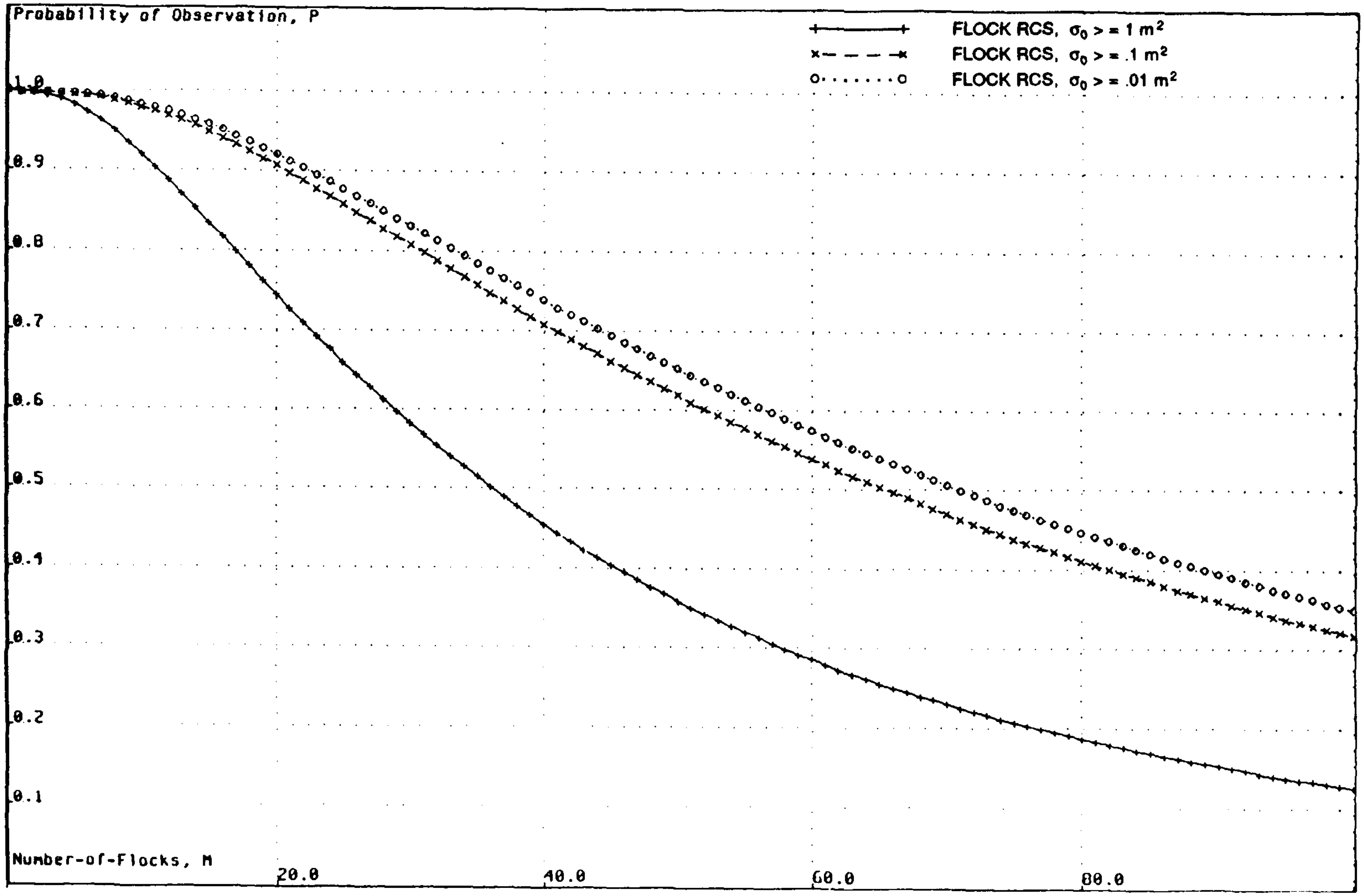

Figure 4a14. Probability of Observing, During Peak Migration, at Least M Flocks With a Mean Radar Cross Section Equal to or Greater Than a Specified Value, σ_0. Central Canada ---- Fall ---- Eider.

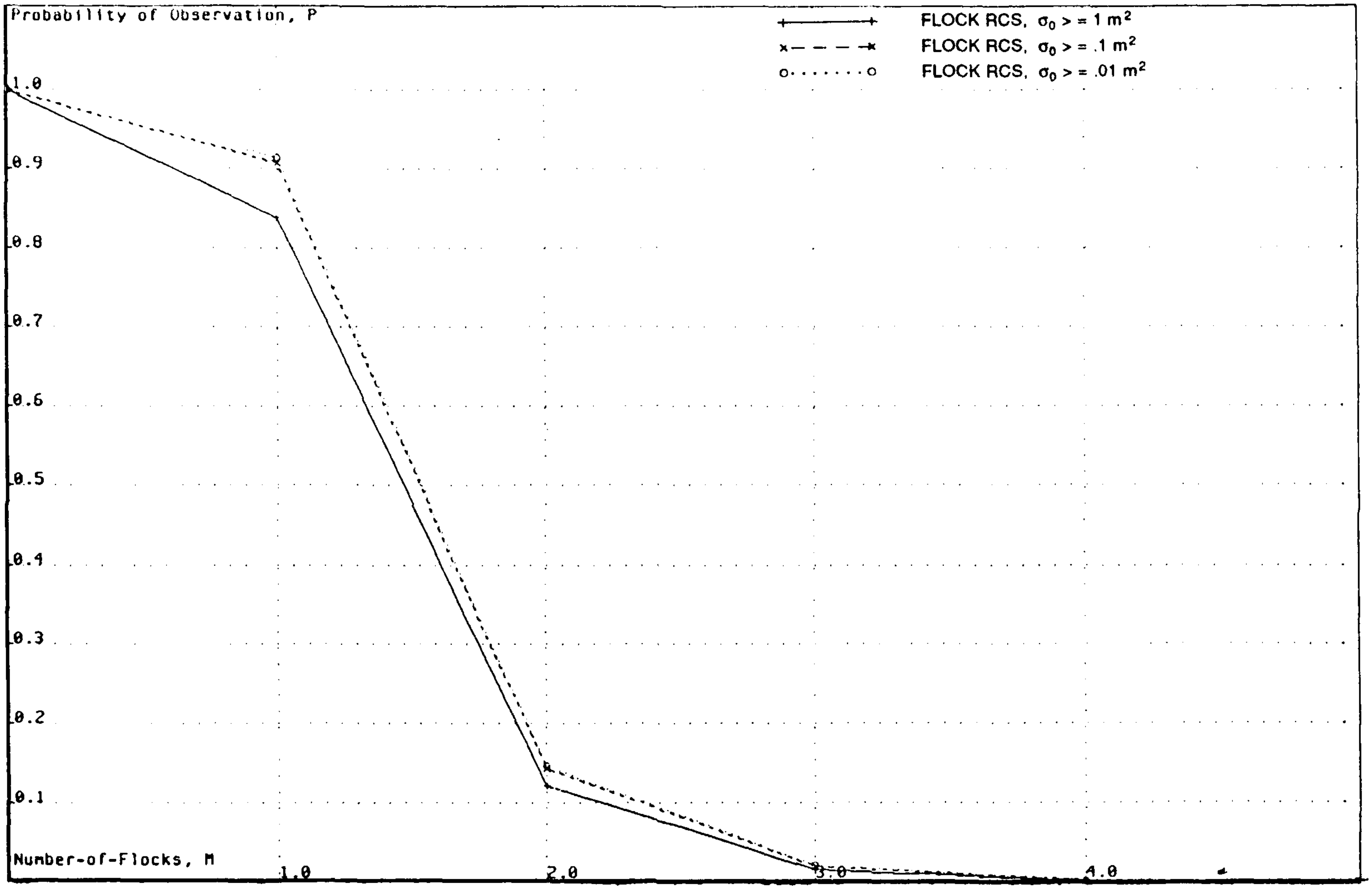

Figure 4a15. Probability of Observing, During Peak Migration, at Least M Flocks With a Mean Radar Cross Section Equal to or Greater Than a Specified Value, σ_0. Central Canada ---- Fall ---- Lesser Snow Goose.

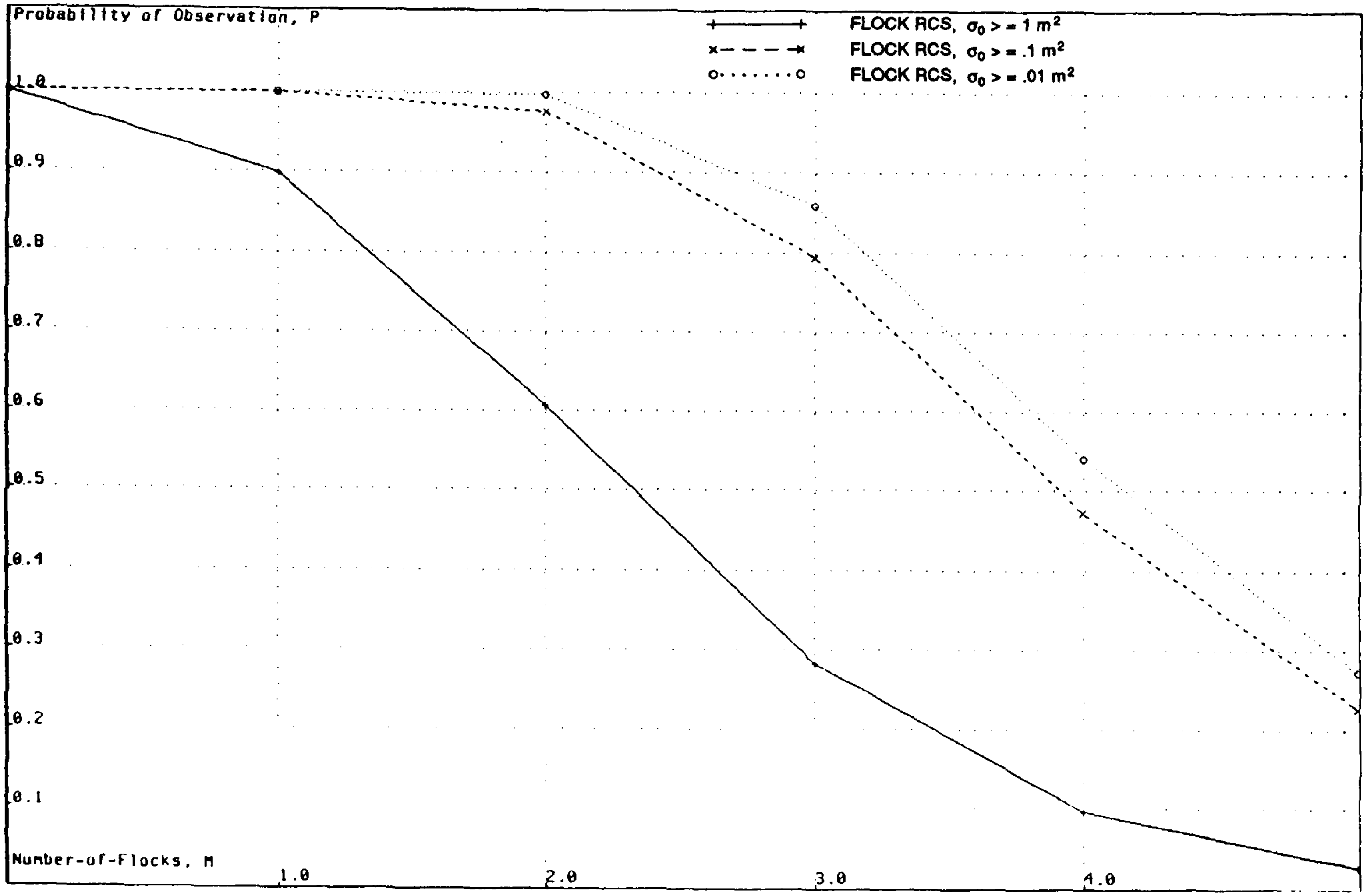

Figure 4a16. Probability of Observing, During Peak Migration, at Least M Flocks With a Mean Radar Cross Section Equal to or Greater Than a Specified Value, σ_0. Central Canada ---- Fall ---- White Fronted Goose.

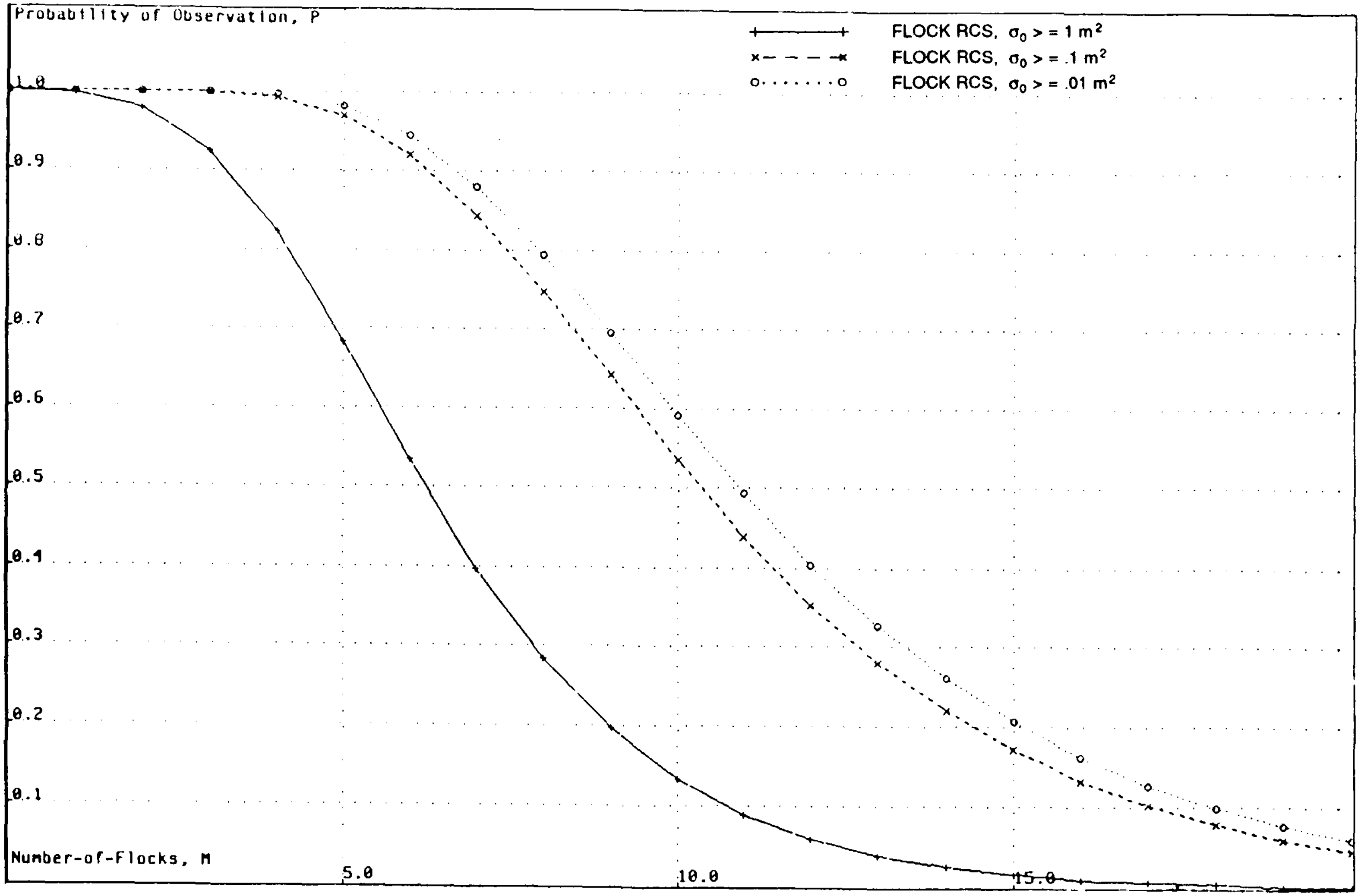

Figure 4a17. Probability of Observing, During Peak Migration, at Least M Flocks With a Mean Radar Cross Section Equal to or Greater Than a Specified Value, σ_0. Central Canada ---- Fall ---- Oldsquaw.

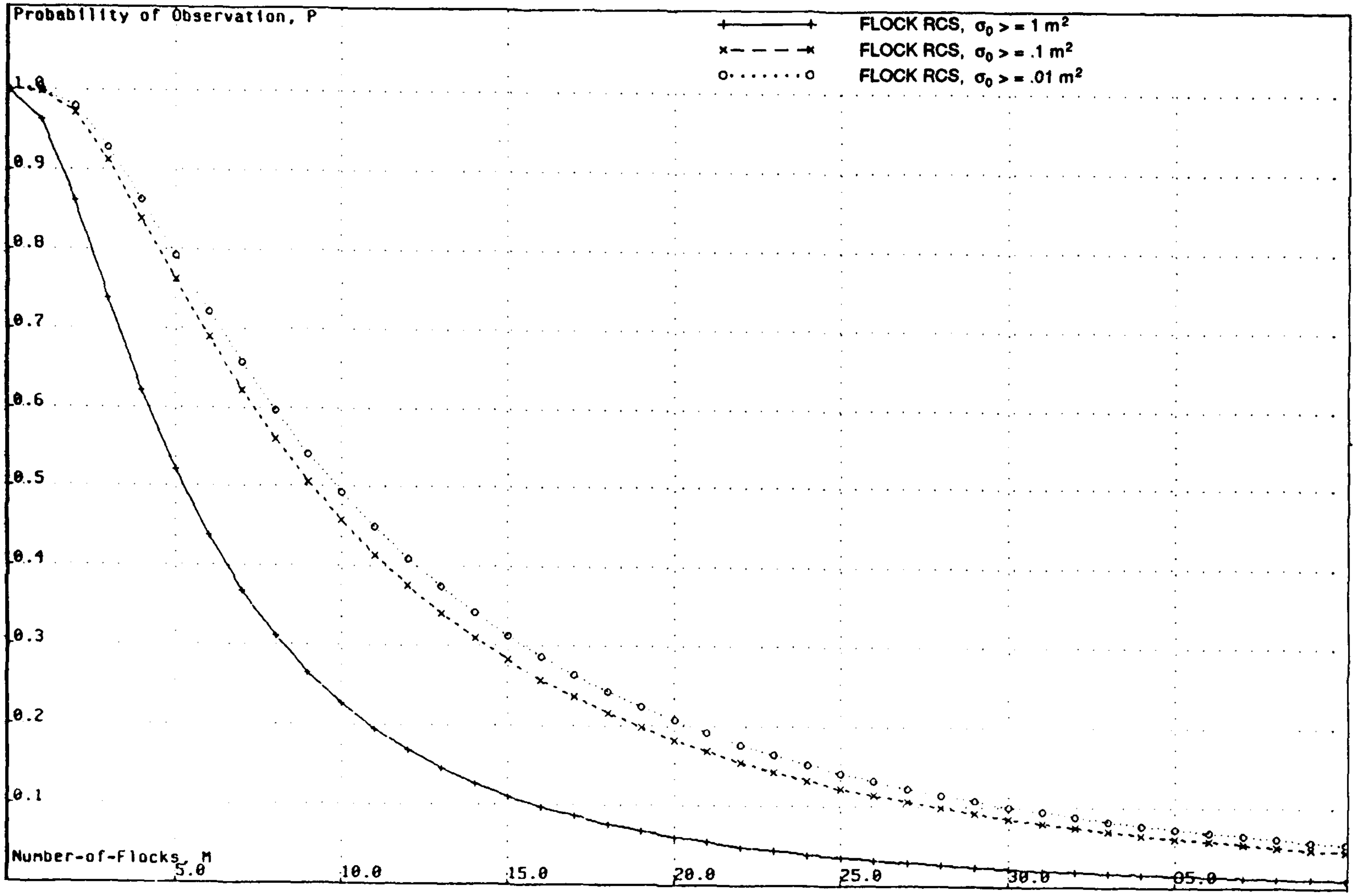

Figure 4a18. Probability of Observing, During Peak Migration, at Least M Flocks With a Mean Radar Cross Section Equal to or Greater Than a Specified Value, σ_0. Eastern Canada ---- Fall ---- Eider.

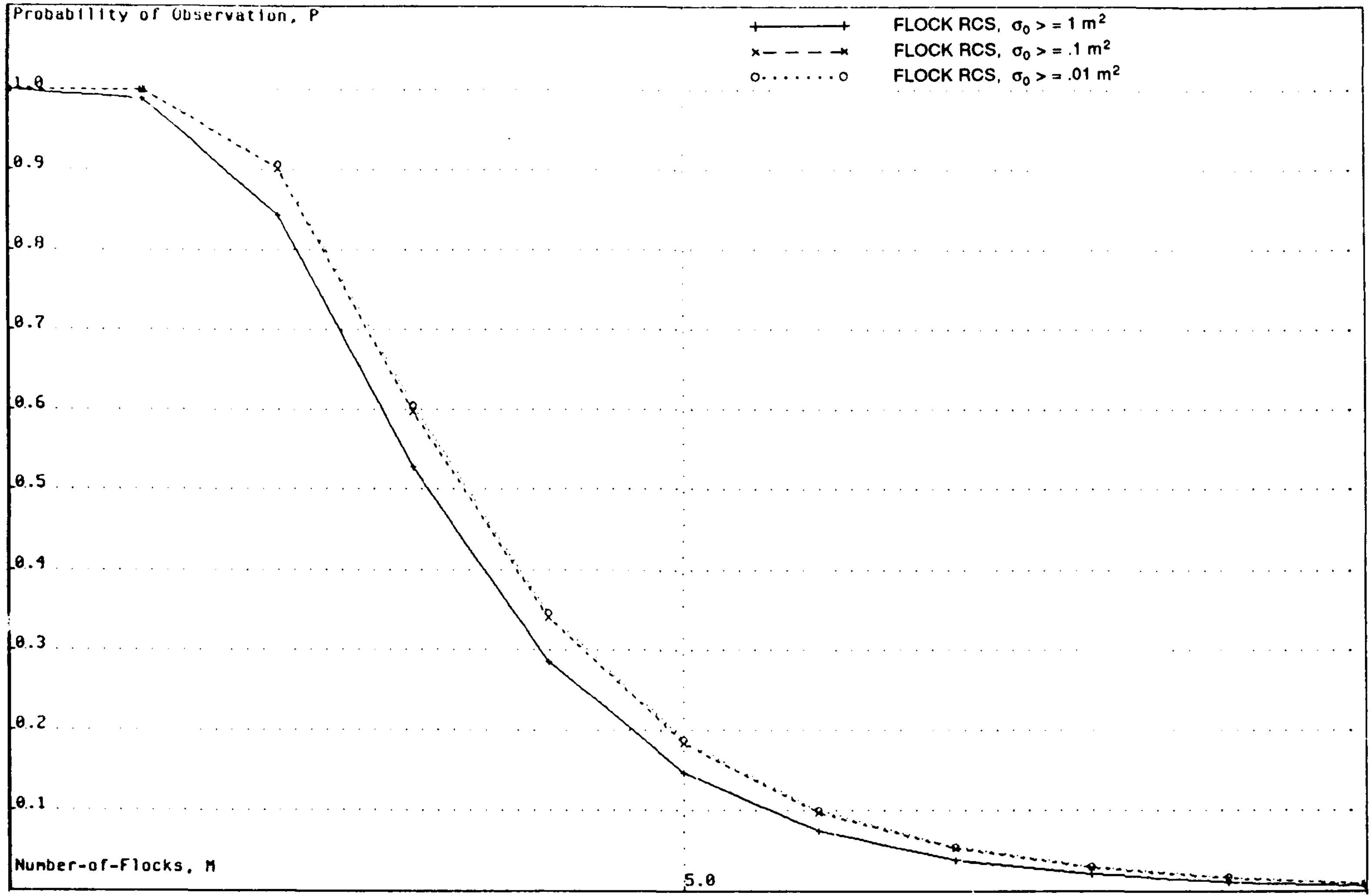

Figure 4a19. Probability of Observing, During Peak Migration, at Least M Flocks With a Mean Radar Cross Section Equal to or Greater Than a Specified Value, σ_0. Eastern Canada ---- Fall ---- Lesser Snow Goose.

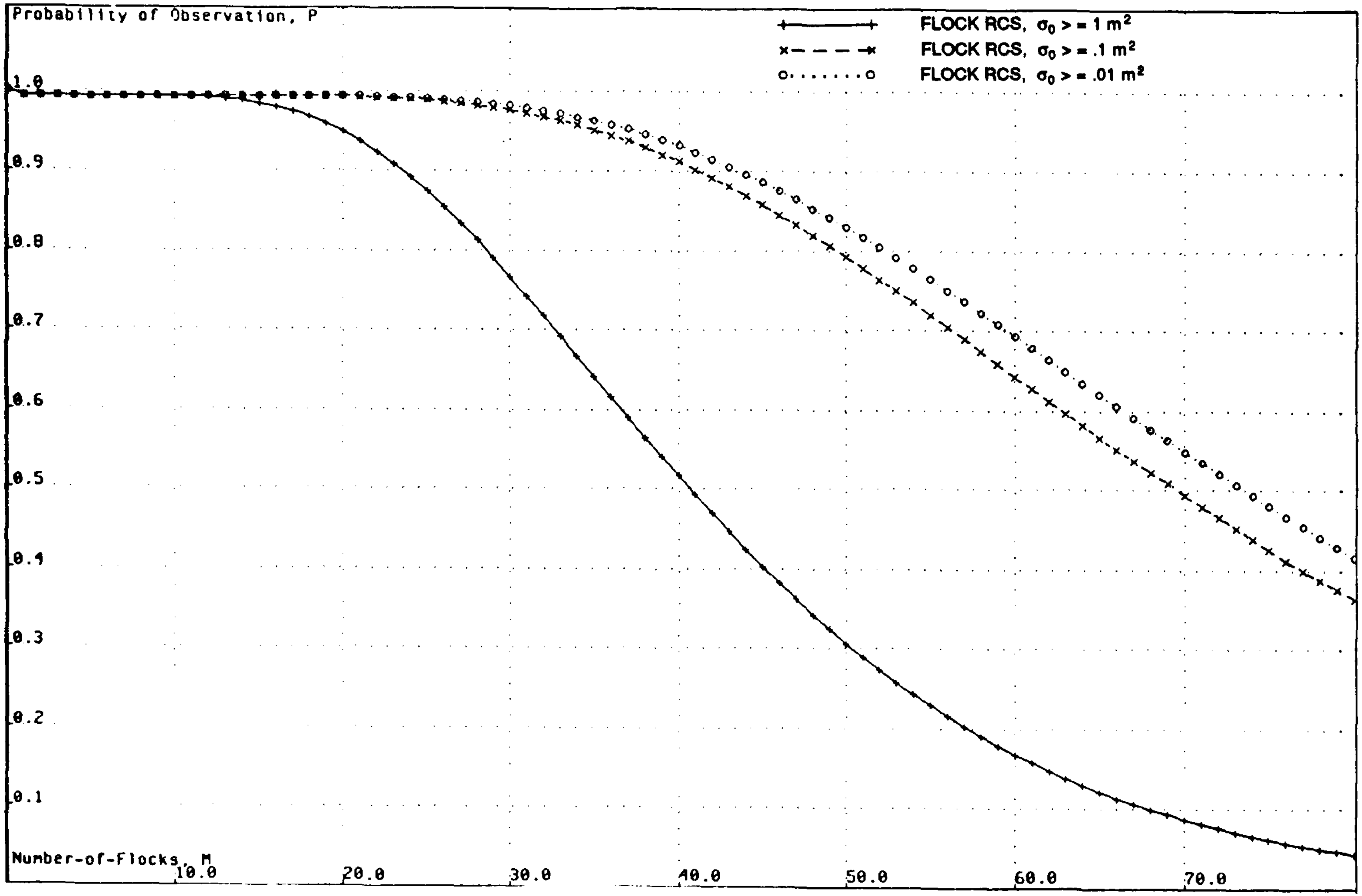

Figure 4a20. Probability of Observing, During Peak Migration, at Least M Flocks With a Mean Radar Cross Section Equal to or Greater Than a Specified Value, σ_0. Eastern Canada ---- Fall ---- Oldsquaw.

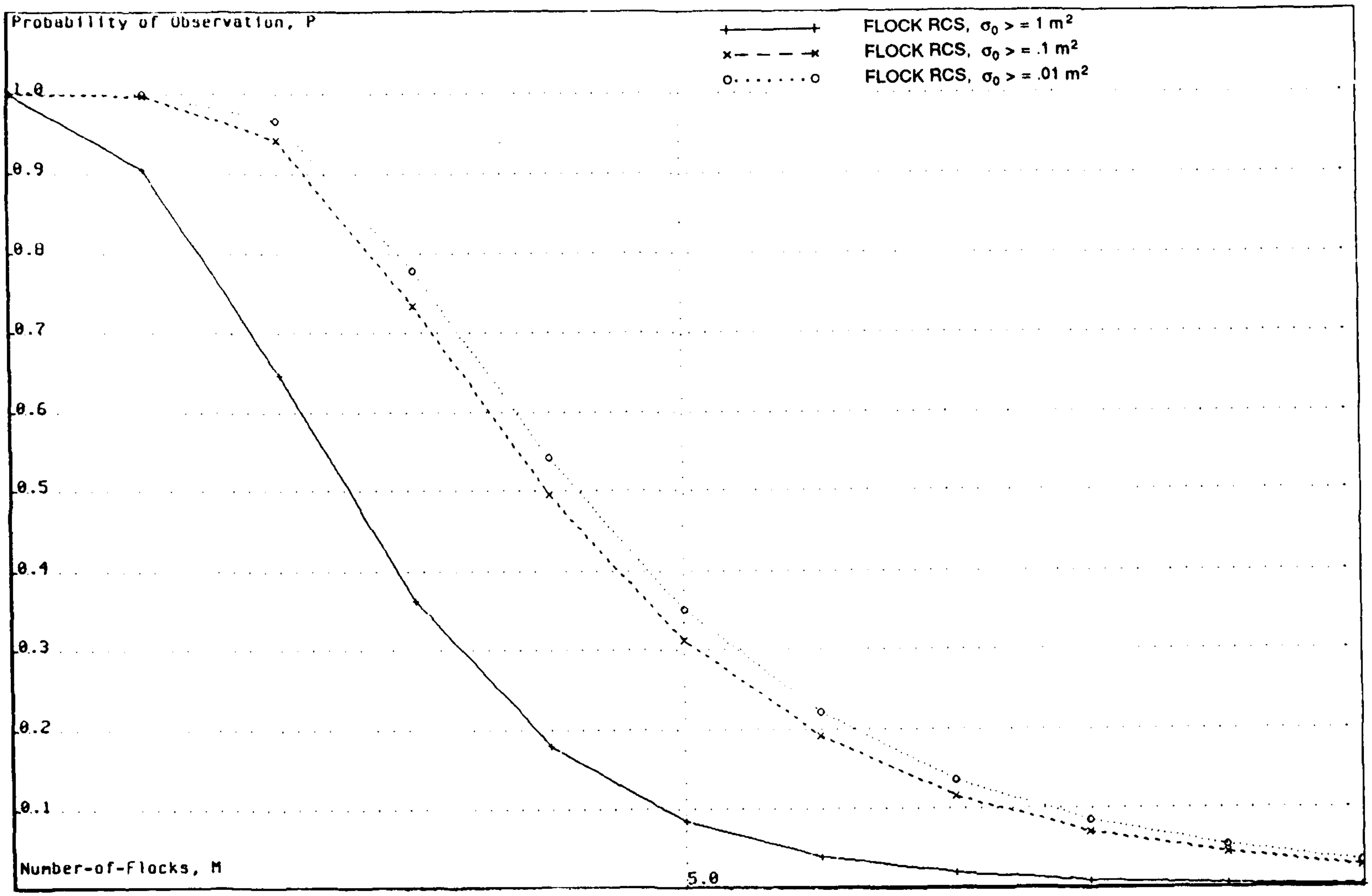

Figure 4a21. Probability of Observing, During Peak Migration, at Least M Flocks With a Mean Radar Cross Section Equal to or Greater Than a Specified Value, σ_0. Eastern Canada ---- Fall ---- Whistling Swan.

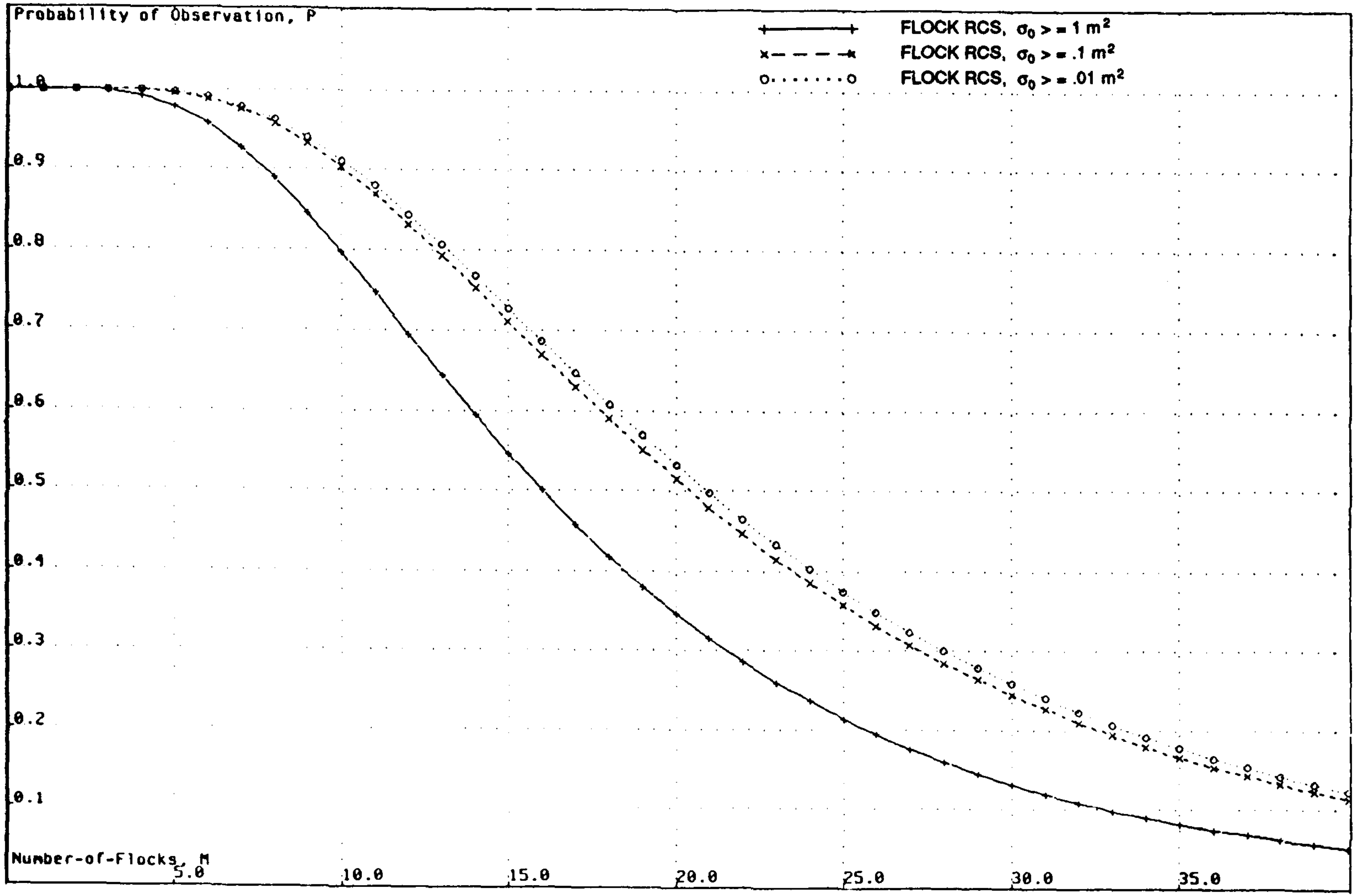

Figure 4a22. Probability of Observing, During Peak Migration, at Least M Flocks With a Mean Radar Cross Section Equal to or Greater Than a Specified Value, σ_0. Eastern Canada ---- Fall ---- Greater Snow Goose.

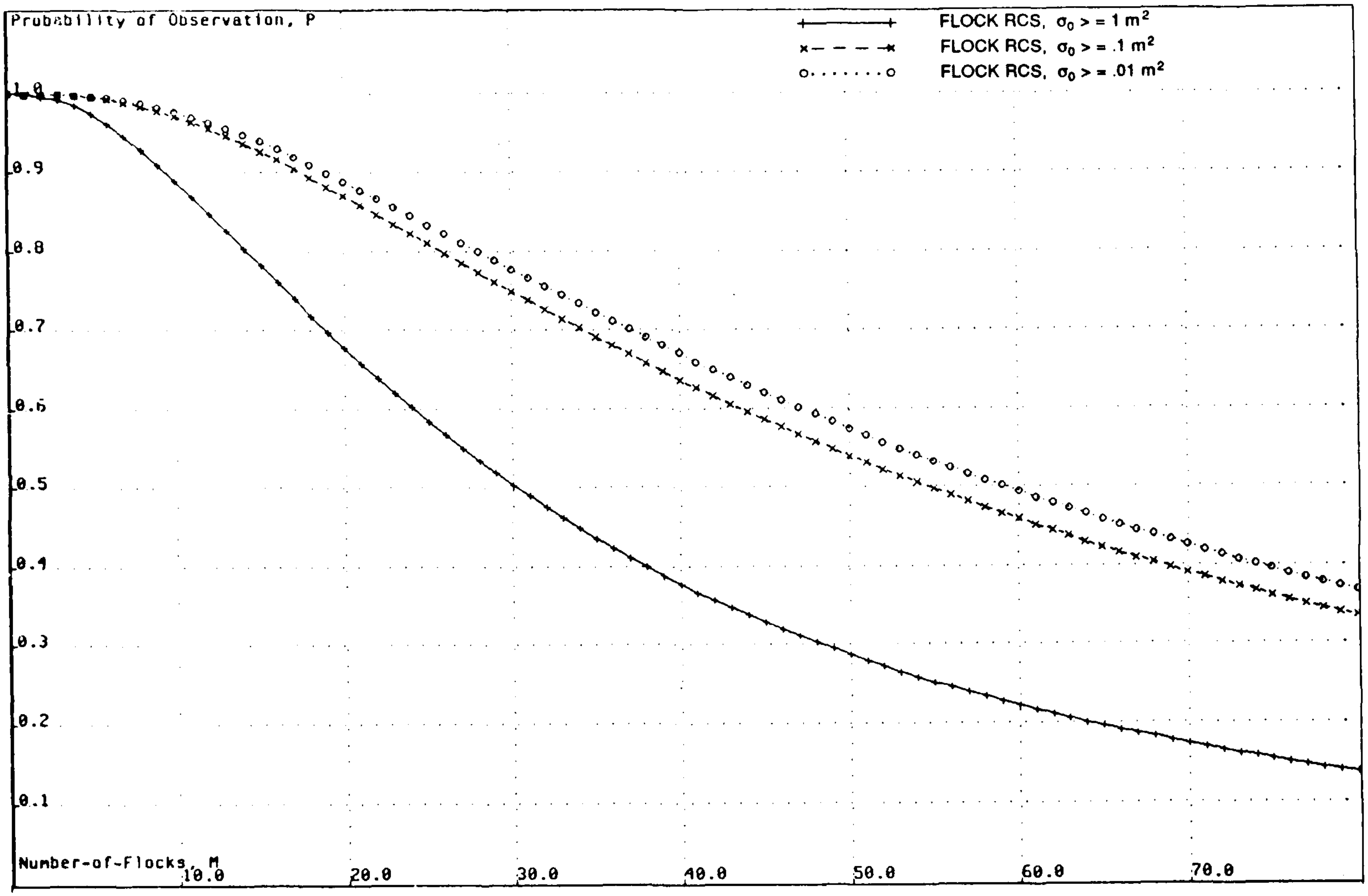

Figure 4b1. Probability of Observing, During Peak Migration, at Least M Flocks With a Mean Radar Cross Section Equal to or Greater Than a Specified Value, σ_0. North Alaska ---- Spring ---- Eider.

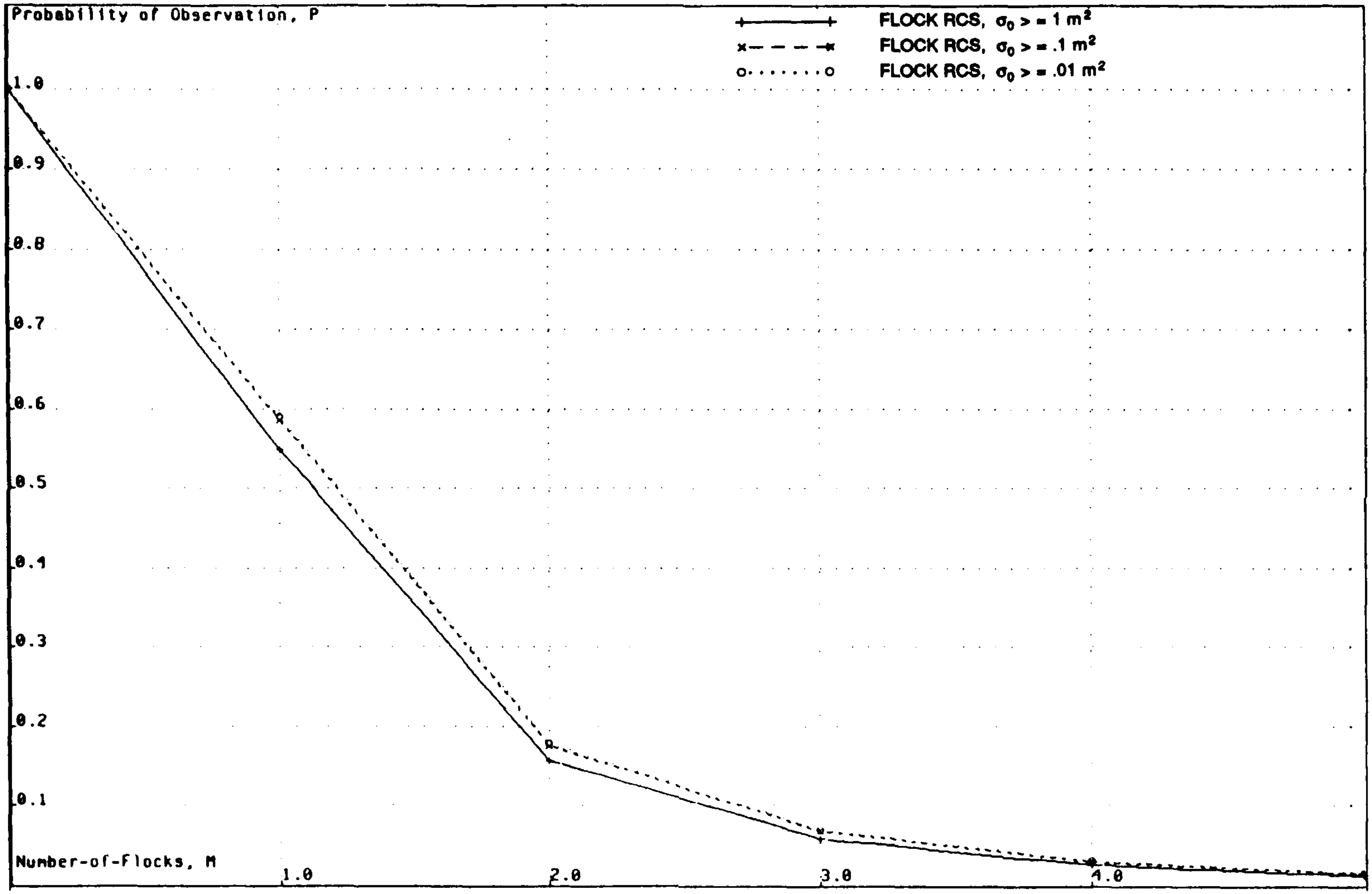

Figure 4b2. Probability of Observing, During Peak Migration, at Least M Flocks With a Mean Radar Cross Section Equal to or Greater Than a Specified Value, σ_0. North Alaska ---- Spring ---- Brant.

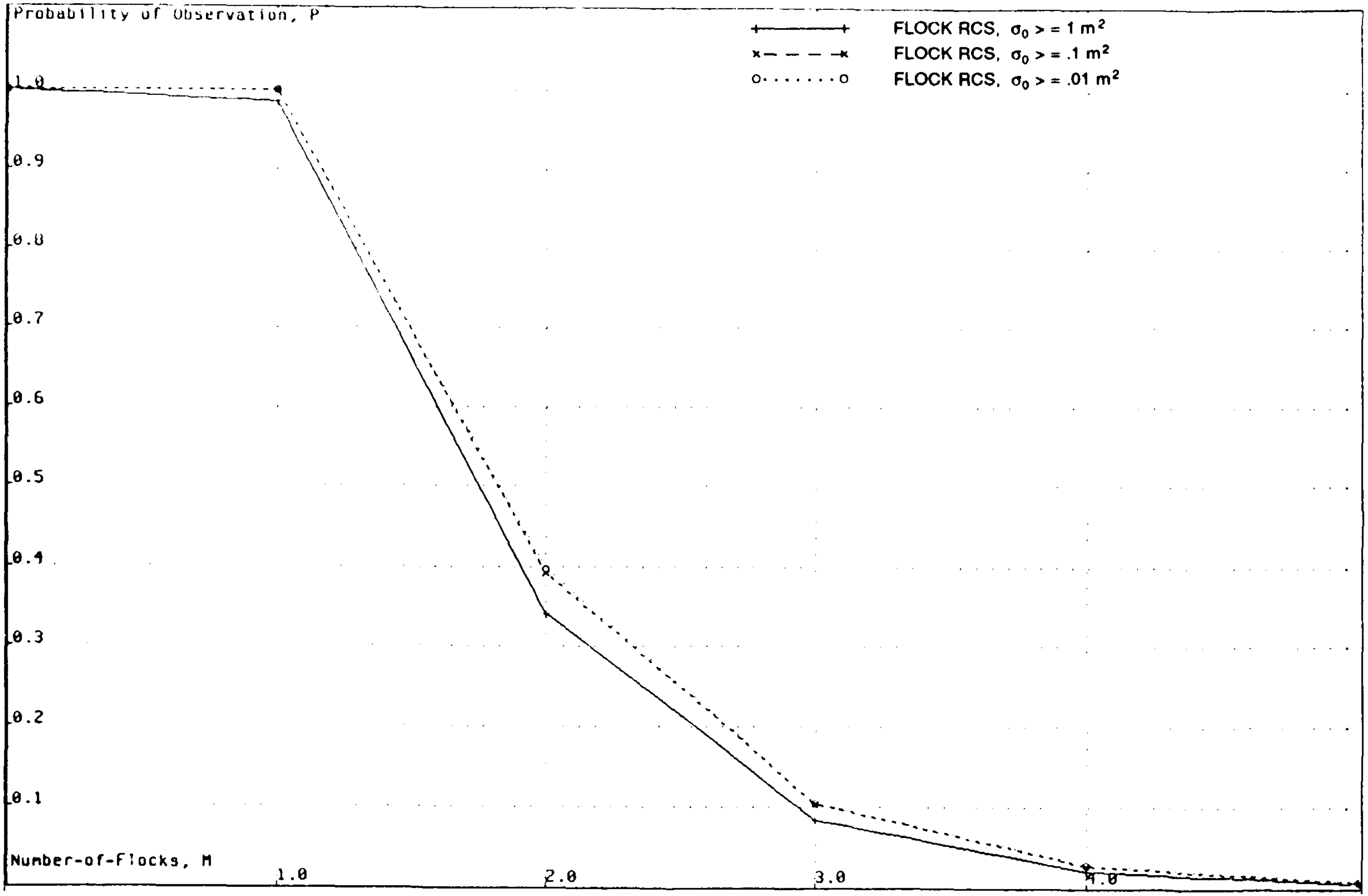

Figure 4b3. Probability of Observing, During Peak Migration, at Least M Flocks With a Mean Radar Cross Section Equal to or Greater Than a Specified Value, σ_0. North Alaska ---- Spring ---- Lesser Snow Goose.

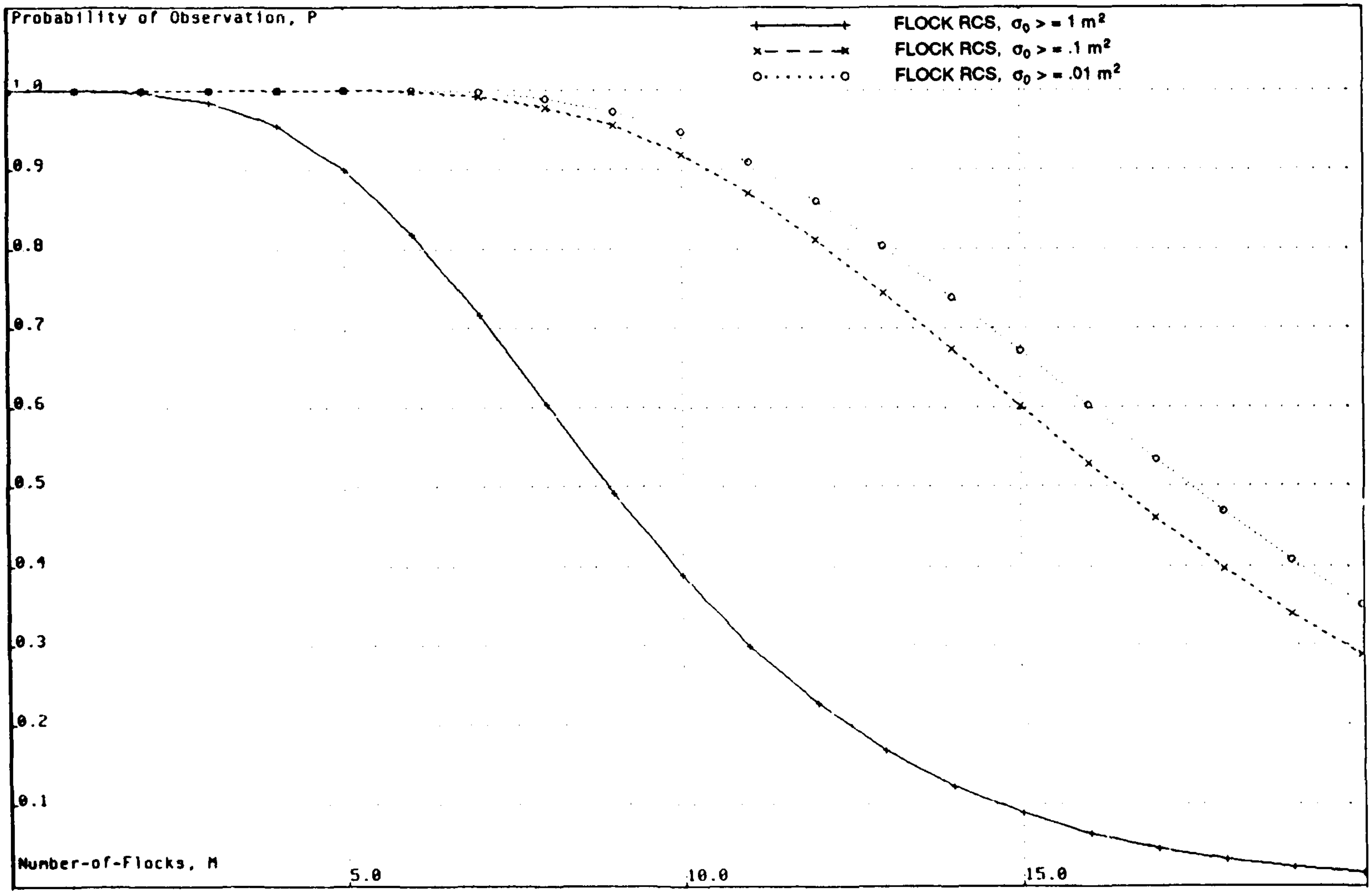

Figure 4b4. Probability of Observing, During Peak Migration, at Least M Flocks With a Mean Radar Cross Section Equal to or Greater Than a Specified Value, σ_0. North Alaska ---- Spring ---- White Fronted Goose.

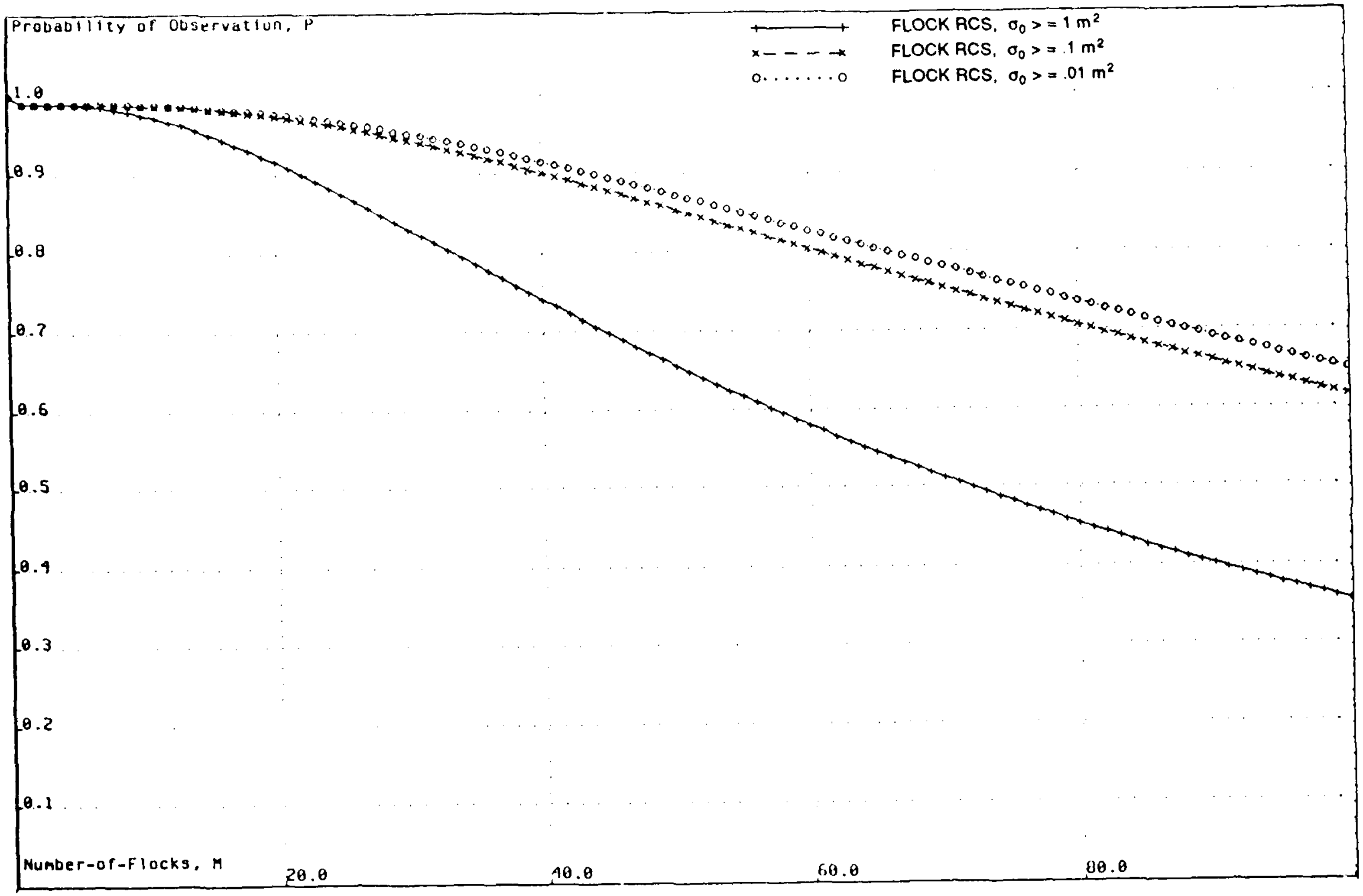

Figure 4b5. Probability of Observing, During Peak Migration, at Least M Flocks With a Mean Radar Cross Section Equal to or Greater Than a Specified Value, σ_0. Western Canada ---- Spring ---- Eider.

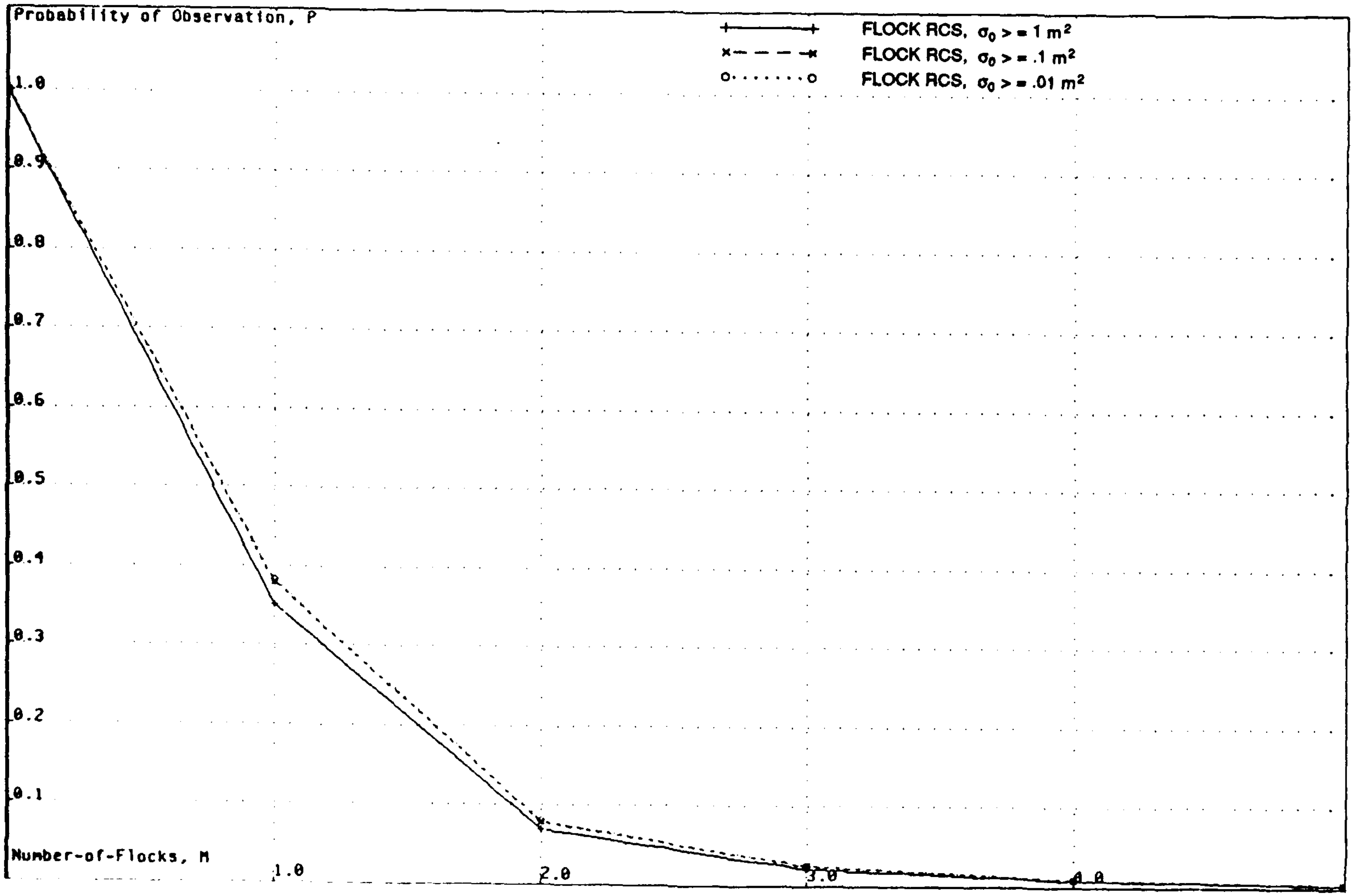

Figure 4b6. Probability of Observing, During Peak Migration, at Least M Flocks With a Mean Radar Cross Section Equal to or Greater Than a Specified Value, σ_0. Western Canada ---- Spring ---- Brant.

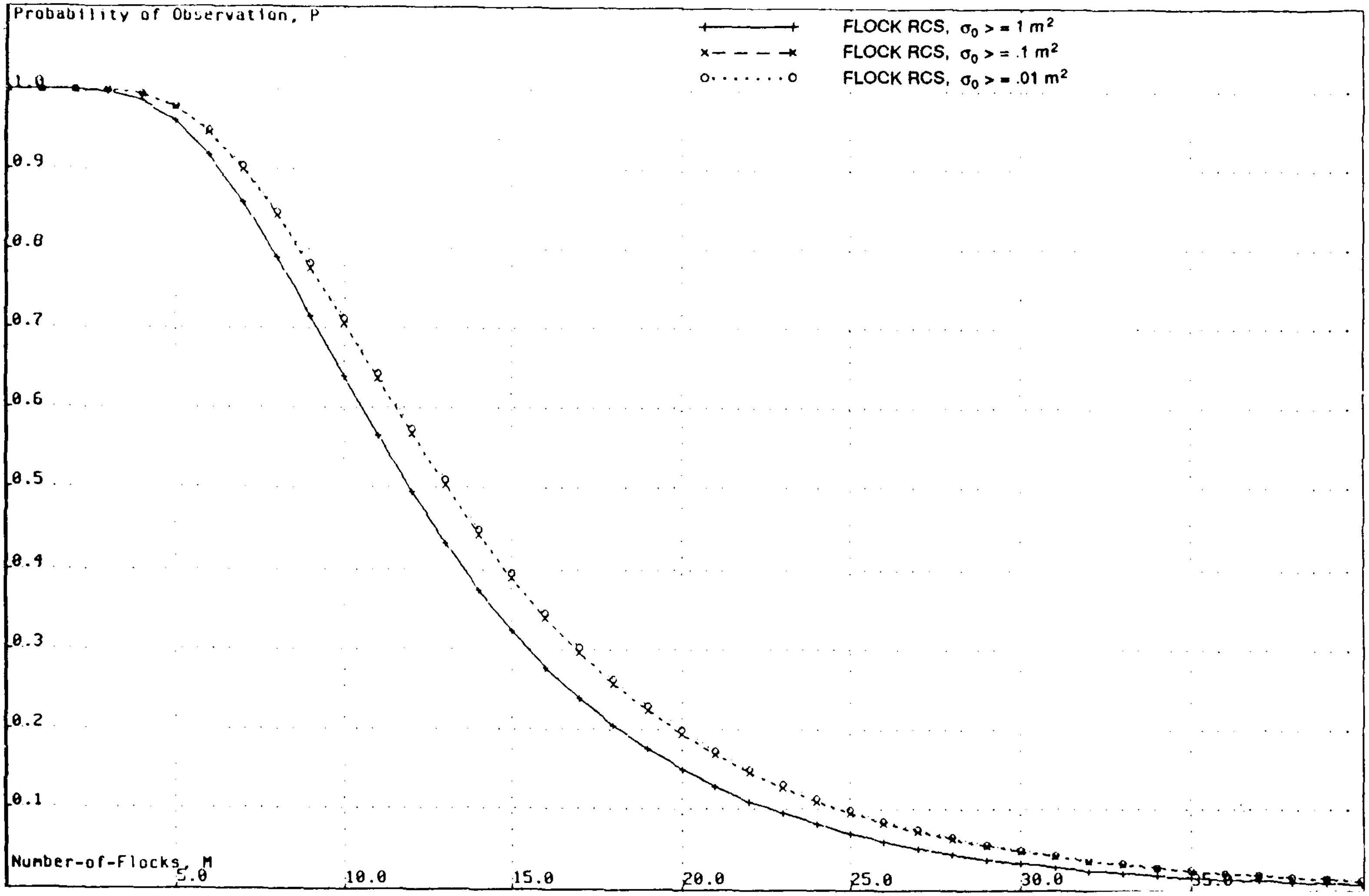

Figure 4b7. Probability of Observing, During Peak Migration, at Least M Flocks With a Mean Radar Cross Section Equal to or Greater Than a Specified Value, σ_0. Western Canada ---- Spring ---- Lesser Snow Goose.

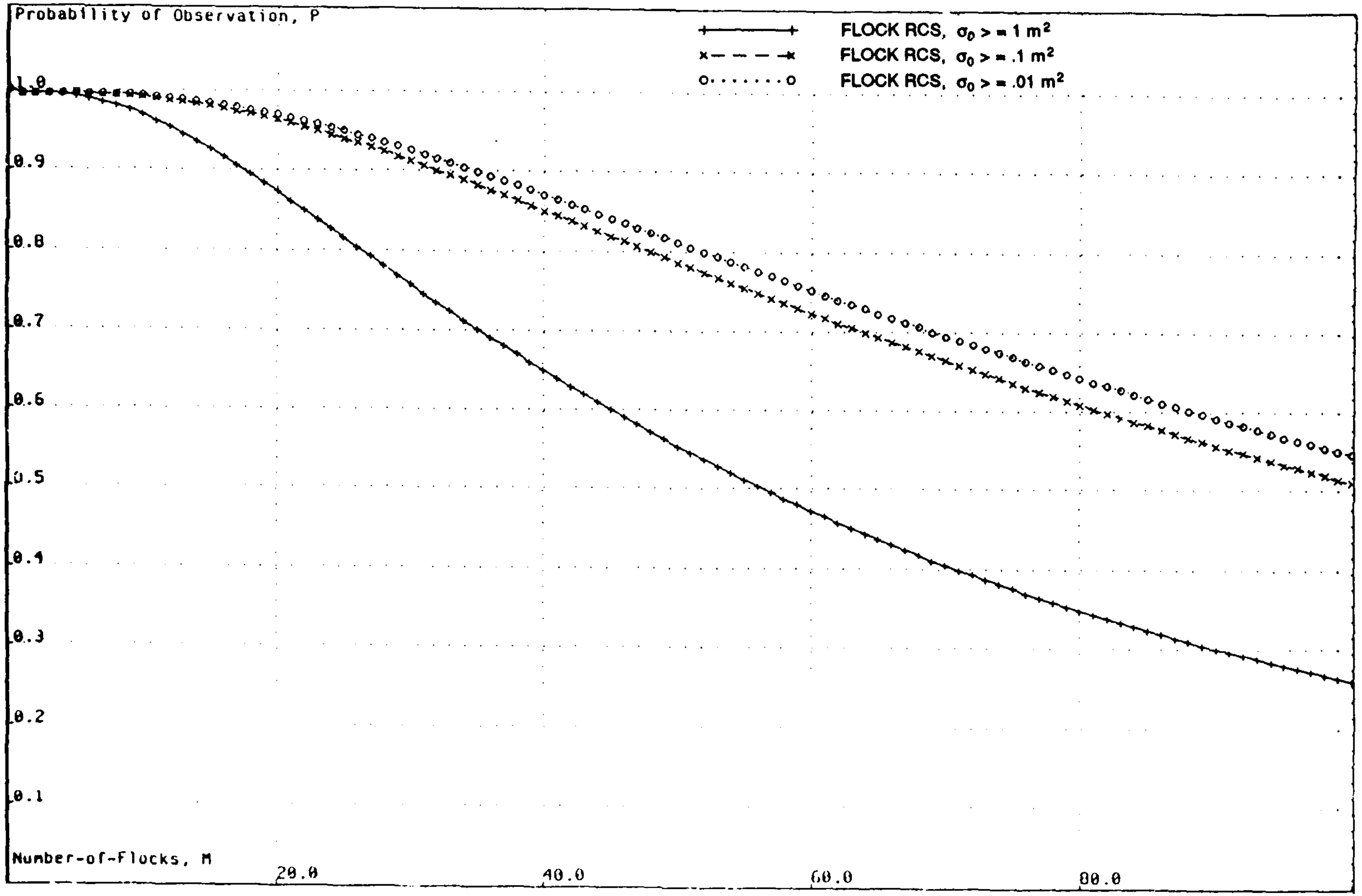

Figure 4b8. Probability of Observing, During Peak Migration, at Least M Flocks With a Mean Radar Cross Section Equal to or Greater Than a Specified Value, σ_0. Central Canada ---- Spring ---- Eider.

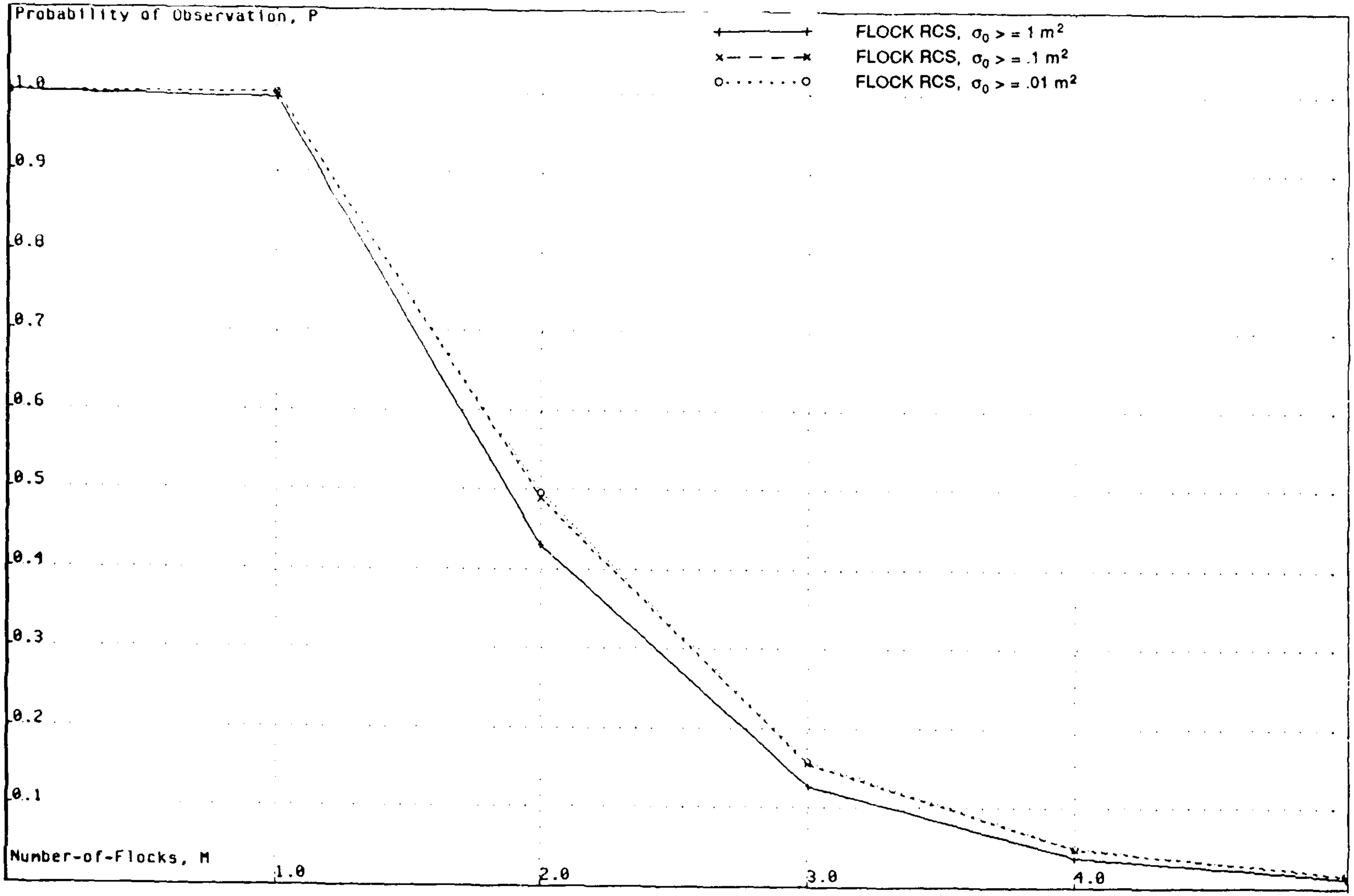

Figure 4b9. Probability of Observing, During Peak Migration, at Least M Flocks With a Mean Radar Cross Section Equal to or Greater Than a Specified Value, σ_0. Central Canada ---- Spring ---- Lesser Snow Goose.

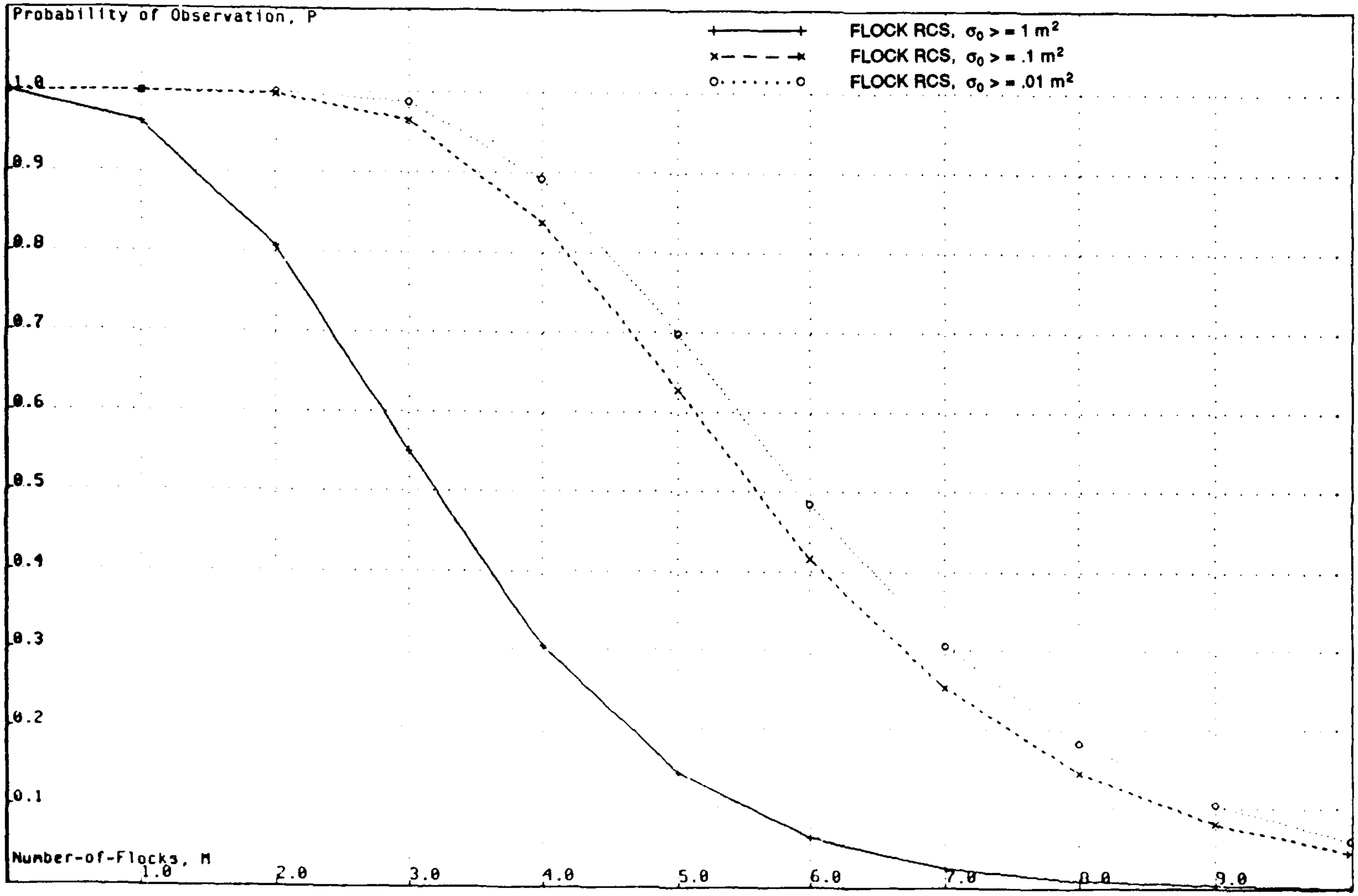

Figure 4b10. Probability of Observing, During Peak Migration, at Least M Flocks With a Mean Radar Cross Section Equal to or Greater Than a Specified Value, σ_0. Central Canada --- Spring ---- White Fronted Goose.

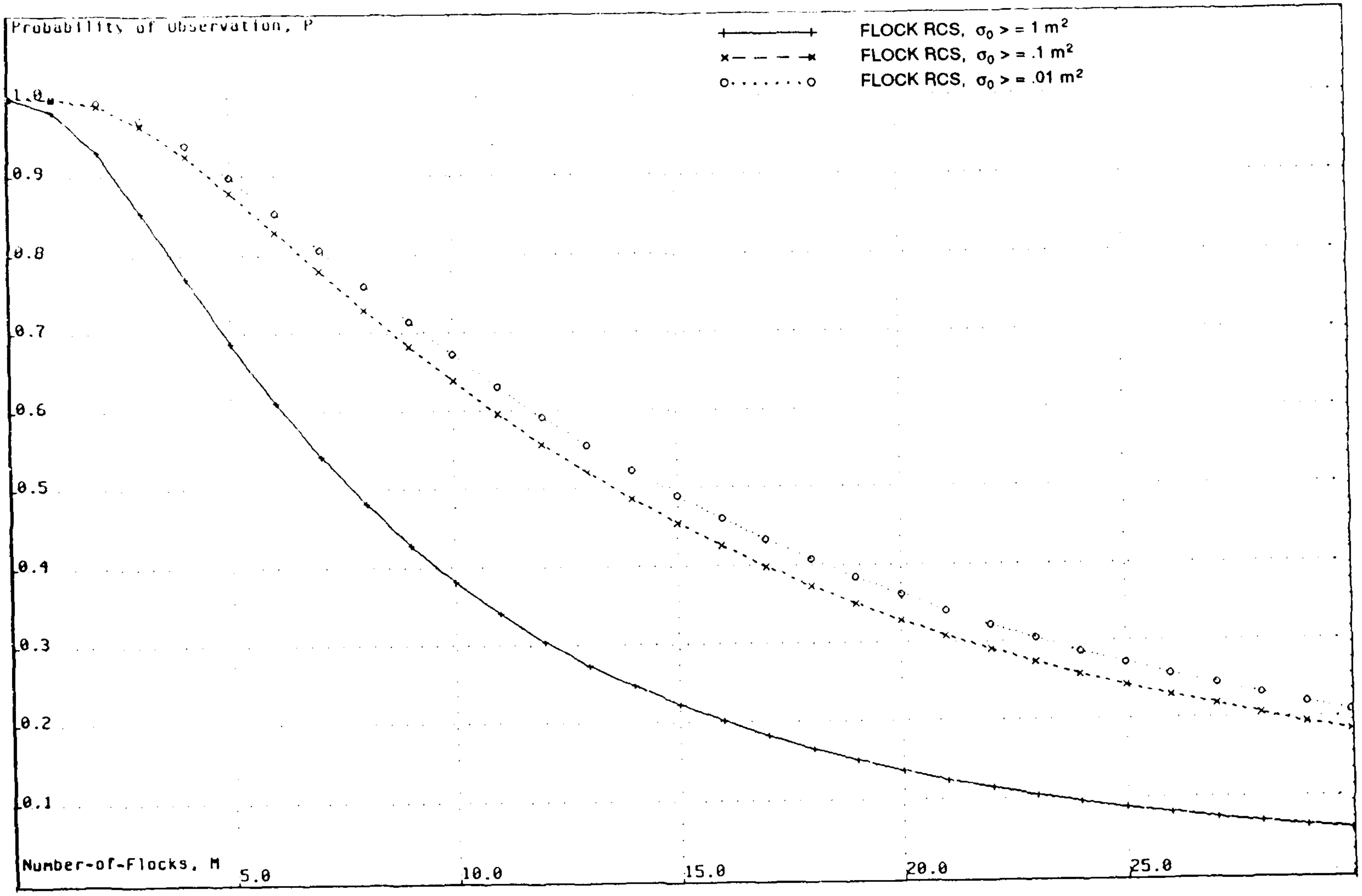

Figure 4b11. Probability of Observing, During Peak Migration, at Least M Flocks With a Mean Radar Cross Section Equal to or Greater Than a Specified Value, σ_0. Eastern Canada ---- Spring ---- Eider.

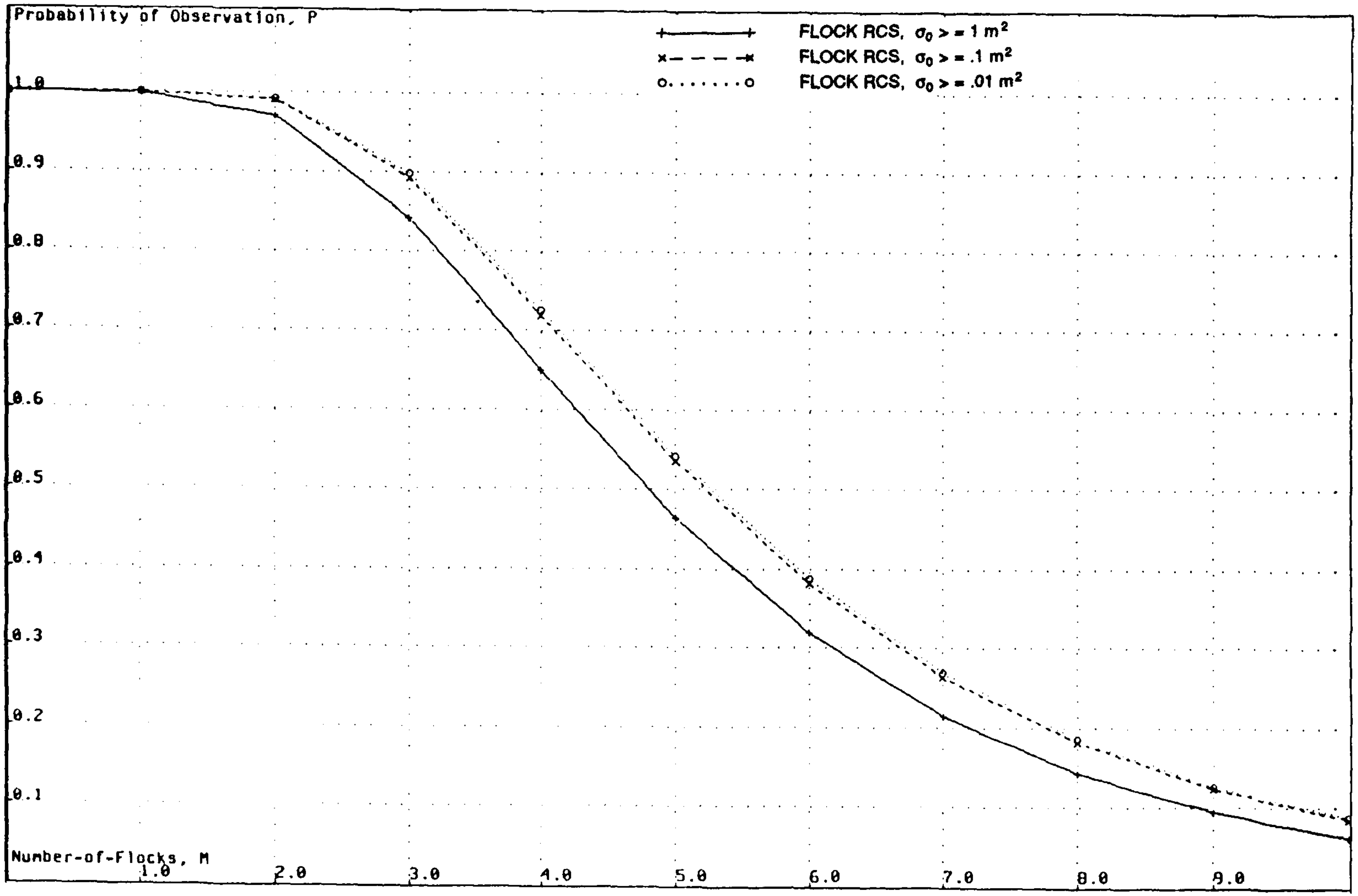

Figure 4b12. Probability of Observing, During Peak Migration, at Least M Flocks With a Mean Radar Cross Section Equal to or Greater Than a Specified Value, σ_0. Eastern Canada ---- Spring ---- Lesser Snow Goose.

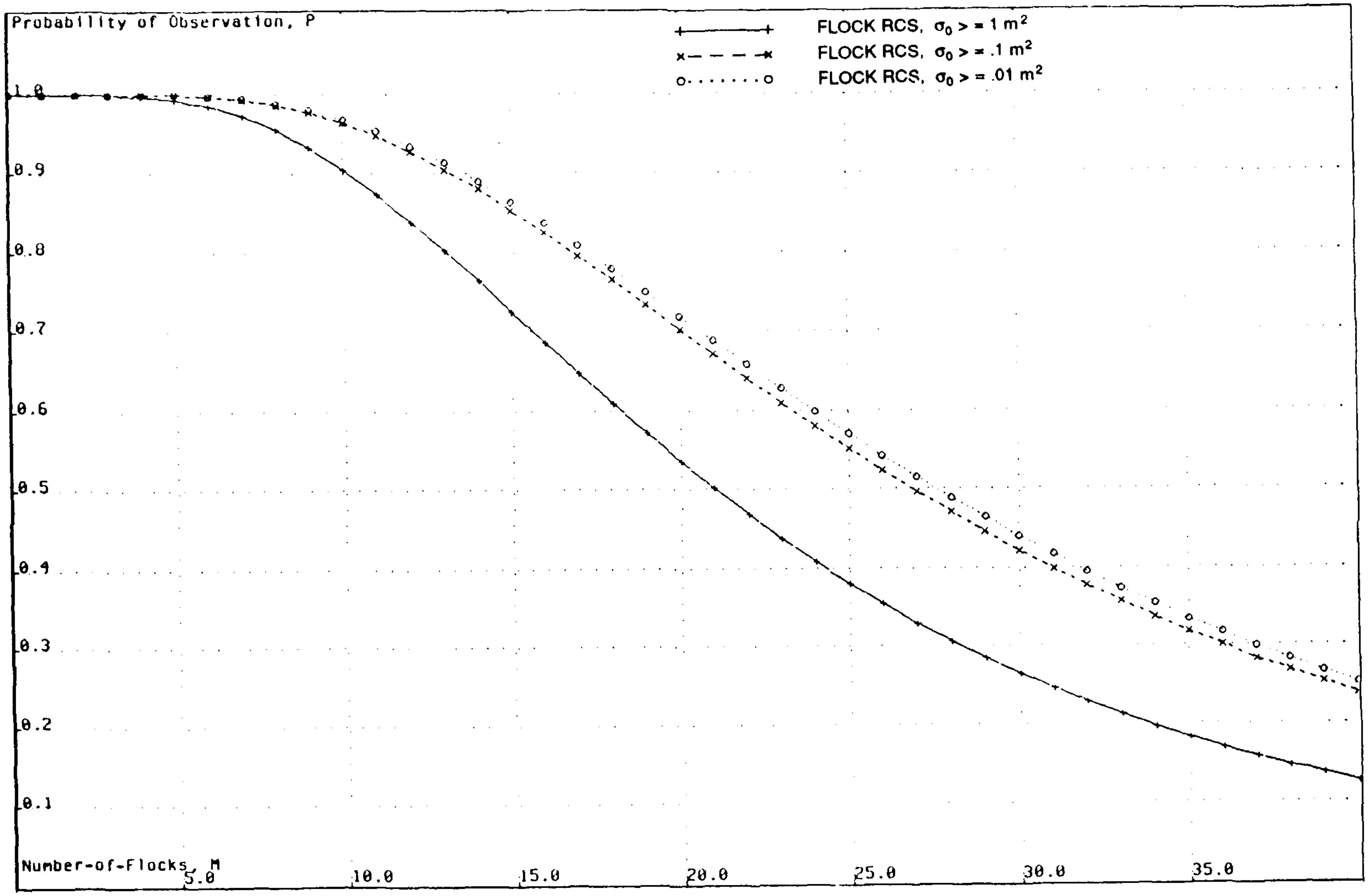

Figure 4b13. Probability of Observing, During Peak Migration, at Least M Flocks With a Mean Radar Cross Section Equal to or Greater Than a Specified Value, σ_0. Eastern Canada ---- Spring ---- Greater Snow Goose.

5. DISCUSSION

An attempt has been made here to express radar bird clutter at the DEW line in probabilistic terms. Quantified data on birds, such as their numbers, and spatial and time movements are difficult to pinpoint, and when given, are presented as estimates in broad terms. The information is inaccurate, and besides, much of the data would often vary from one period of time to another.

The emphasis in this report is not so much on obtaining bird data, but on the approach to express bird parameters and observations in analytical form. The data can always be updated and improved upon, and then be used to feed the equations and adjust the curves. This approach is also applicable to looking at the early or later times of the migration period. Curves can be generated that apply to this period by changing the value of the number of birds per day. To a limited degree, we considered the effect of frequency, and found that, in the Rayleigh region, the RCS of a bird σ_1, increases when going from L-band to UHF frequency. The effect on the probability curves can be seen by considering Eq. (26), which is the probability L that a flock has a specified cross section σ_0 . L is a function of σ_0 / σ_1. Therefore, when σ_1 is tripled, as happens in the Rayleigh region in our case, then it has the same effect as dividing σ_0 by 3. This effect is carried over to the probability curves for P. If σ_1 is three times larger, then the curve for $\sigma_0 = 1$ will lie close to the $\sigma_0 = 0.1$ curve shown (actually it would coincide with a σ_0=.33 curve). However, the curves will still approach the same limit of σ_0=0.01. The effect is to substantially raise the probability. We must add that, in this report, we did concentrate on the larger birds, which may have conveyed the appearance that there are less than a dozen species moving about in the arctic. There are also numerous smaller species of birds there; however, they may not generally contribute significantly to radar clutter. This may be true not only because of their individual size, but also because they do not normally travel in big defined flocks during migration as the larger birds do. [Since this may not always be true, it would be a worthwhile study to see which other birds may present a radar clutter problem].

The present effort considered the effect of each individual species. This means, in some circumstances, one would have to know the species being dealt with, and, therefore, presupposes that the bird could be identified. The next step, in the continuation of this effort, is to be able to make predictions without having to identify the kind of bird. The probability of observing a particular RCS would depend on the period of time and the place, and would sum up the effect of the expected relevant birds. It would then be unnecessary to have a plot for each individual species. This would consolidate the graphs and result in a considerably reduced number of graphs.

The approach in this report can be a guide for studying conditions other than migration. Birds are present at staging and breeding areas for much of the year. In these areas, their flights are more sporadic and their flock characteristics are less defined. Adjustments to the equations would have to be made to handle these conditions.

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